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AUTOIONIZING STATES IN HIGHLY IONIZED OXYGEN, FLUORINE AND SILICON*

J. P. Forester, R. S. Peterson, P. M. Griffin, D. J. Pegg,
H. H. Haselton, K. H. Liao, I. A. Sellin, J. R. Mowat,
and R. S. Thoe

University of Tennessee, Knoxville, Tennessee 37916

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

INTRODUCTION

Excitation processes in atoms or ions usually involve the promotion of one of the least tightly bound outer shell electrons to a higher orbital leading to a state lying below the ionization threshold. It is possible however to form highly excited discrete states that are embedded in the continuum if one or more inner core electrons are raised to outer shells. In the present paper we report on such states in high Z 3-electron ions associated with core excited configurations of the type $1s2sn\ell$ and $1s2pn\ell$. Such states may autoionize rapidly via the Coulomb interaction unless forbidden to do so by selection rules on this process. These metastable autoionizing states either decay by radiation or autoionize at a slower rate via the weaker magnetic interactions. The lowest lying quartet state in 3-electron ions $(1s2s2p)^4P_{5/2}^o$, is metastable against both autoionization and radiation. Our previously measured lifetimes [1] for this state (in nanoseconds) are: S (1.1), Si (2.1), Ar (0.66), Cl (0.91), F (15), and O (25). Radiative decay processes involving core-excited states have also been previously observed. For example, one type of decay is an E1 transition between two metastable quartet states and another is a similar transition from a core excited state to a singly excited state. The probability of this latter transition increases as Z^4 and thus competes favorably with allowed autoionization for the depopulation of such states in higher Z ions.

EXPERIMENTAL METHOD

In the present experiment the electron decay-in-flight spectra of lithium-like O, F, and Si have been studied, using high energy beams from the Oak Ridge National Laboratory tandem accelerator. A thin carbon foil placed upstream of the viewing region of the analyzer served to both strip and excite the beam ions. The incident energy of the beam was chosen to maximize as far as possible the desired charge state downstream of the foil target. The ejected electrons were collected and energy analyzed using a second order, double focusing electrostatic cylindrical mirror analyzer, a schematic diagram of which is shown in Figure 1. This analyzer has a viewing region of 0.15 mm of the excited beam. The mean polar acceptance angle of the instrument is 42.3 degrees with a spread of ± 0.09 degrees. Electrons passing through the analyzer are detected by a low noise channeltron electron multiplier situated behind the exit slit. Spectra were obtained by sweeping the voltage on the analyzer using a linear ramp offset by a preset D.C. level. The

ORNL-DWG 73-1405

Figure 1. Schematic of the apparatus showing the electron analyzer.

spectra were then accumulated in a multichannel analyzer. The position of the foil with respect to the spectrometer viewing region could be varied in order to differentiate between short and long lived states thus aiding in the identification of the peaks.

The primary purpose of this experiment was to improve on the spectral resolution obtained in previous measurements [1] on F and O as well as to study analogous states in Si. The instrumental resolution was improved by the use of a new and larger analyzer (described previously) and by the use of thinner carbon foil targets (nominal thicknesses $2\mu\text{g}/\text{cm}^2$) to reduce energy straggling and multiple scattering effects. The spectrometer was calibrated using Auger electrons emitted from inert gases excited by electron impact. In these spectra the measured resolution was better than 0.3%. The well established Auger energies of Werme, Bergmark, and Siegbahn [2] were used to obtain the analyzer constant.

RESULTS

Figure 2 shows the spectra of autoionization electrons emitted in flight by a 6.75 MeV highly stripped O beam following passage through a carbon foil of thickness $2\mu\text{g}/\text{cm}^2$. The electron energy scale was established using Holmøien and Geltman's [3] value of 416.2 eV for the energy of the $4p^0(1)$ state. The notation used in this work will be that presented by Holmøien and Geltman [3]. The lower of the upper two spectra corresponds to a time delay of about 0.2 nsec. with respect to the upper. The $4p^0(1) - 4p^e(1)$ splitting of 12.9 ± 0.2 eV measured in the present experiment can be compared with the previously measured value of 12 ± 1 by Pegg et al. [1] and theoretical values of 13.1 [3], 13.0 [4], 12.2 [5], and 14.0 [6] eV. A radiative transition is also possible between these two states for which the measured splitting of 12.9 eV corresponds to a photon wavelength of 961 Å, which to our knowledge has not yet been observed. The partially blended feature on the low energy side of the $4p^e(1)$ peak appears to be associated with the autoionization decay of the $5p^e(1)$ state of 4-electron O. Two possible final states exist for the 3-electron ion $[(1s^2 2p)^2 p^0, (1s^2 2s)^2 s^e]$ leading to the emission of two discrete energy electrons separated by 12 eV. The higher energy of these two transitions appear to be present in our spectrum in the blended feature at 438.7 eV. Another component of this blend is associated with the decay of the $6s^0(1)$ state in 5-electron O to the $(1s^2 2p^2)^3 p^e$ final state of the residual 4-electron ion. Similar lines have recently been observed in the foil excited electron spectra of Be and B by Bruch et al. [7]. The structure at 434.4 eV in our spectra may be associated with the decay of the metastable $2p^e(1)$ state in 3-electron O. The lower spectrum appearing in Figure 2 shows features of higher energy which are the result of autoionizing transitions involving $n \geq 3$. Some of the lines have been identified in Table I. The positions of the

Figure 2. Spectra of electrons from highly stripped O undergoing decay in flight, plotted in the rest frame of the emitting ion. The energy scale is established by assigning a value of 416.2 to the $4p^0(1)$ peak [3]. The continuous curve drawn through the data is drawn to aid the eye.

TABLE I. Electron energies (eV, ionic rest frame)

No. of elect.	Initial state	Final state	OXYGEN		FLUORINE		SILICON	
			Theory ^d	Expt. ⁺	Theory ^d	Expt. ⁺	Theory ^d	Expt. ⁺
3	$4P^o(1)$	$1S^e$	416.2 ^a , 417.3 ^b	416.2 [*]	530.0 ^a , 531.3 ^b	530.0 [*]	1302.9 ^a	1303(2)
4	$5P^e(1)$	$2P^o$	428.3 ^b , 427.1 ^c	426.4(.5)	543.6 ^b	544.1(.7)		
3	$4P^e(1)$	$1S^e$	429.3 ^a , 429.5 ^b	429.4(.2)	545.1 ^a , 545.3 ^b		1326.0 ^a	1325(1)
3	$2D(1)$	$1S^e$					1338.6 ^c	1335(2)
3	$2P^e(1)$	$1S^e$	436.6 ^b		553.7 ^b , 553.6 ^c	552(.2)	1342.5 ^c	1343(2)
5	$6S^o(1)$	$3P^e$	438.8 ^b , 438.2 ^c	438.7(.5)	556.7 ^b , 556.4 ^c	555.5		
4	$5P^e(1)$	$2S^e$	440.3 ^b , 439.1 ^c		557.6 ^b , 556.4 ^c			
							1356(3)	
4	$5S^o(1)$	$2P^o$	444.9 ^b		562.9 ^b , 563.3 ^c	560(.1)		
4	$3S^o(1)$	$2P^o$	453.7 ^b		573.5 ^b	573(.1)		
	$6S^o(1)$	$3P^o$	455.1 ^b		575.9 ^b			
4	$3S^o(1)$	$2S^e$	465.7 ^b		587.5 ^b	586.8(.8)		
3	$4S^e(1)$	$1S^e$	498.0 ^a , 500.2 ^b		638.6 ^a , 641.4 ^b	641(.1)		
4	$5S^e(1)$	$2P^o$	500.5 ^b		641.8 ^b			
3	$4P^o(2)$	$1S^e$	502.3 ^a , 503.9 ^b	502(.1)	643.6 ^a , 645.8 ^b	645.2(.4)		
3	$4P^o(3)$	$1S^e$	508.0 ^a , 508.2 ^b	506.2(.5)	650.1 ^a , 650.3 ^b	648.1(.8)		
3	$4P^e(2)$	$1S^e$	511.3 ^a , 511.5 ^b	311.3 [*]	654.1 ^a , 654.2 ^b	653.1 [*]		
4	$5P^e(4)$	$2P^o$	517.1 ^b	517.3(.4)	661.0 ^b	660(.1.5)		
4	$5P^o(2)$	$2S^e$			661.4 ^b			
4	$5P^e(3)$	$2S^e$	521.5 ^b		665.8 ^b	664(.7)		

TABLE I. Electron energies (eV, ionic rest frame)

No. of elect.	Initial state	Final state	OXYGEN		FLUORINE		SILICON	
			Theory ^d	Expt. ⁺	Theory ^d	Expt. ⁺	Theory ^d	Expt. ⁺
3	4s ^e (3)	1s ^e	527.6 ^a , 529.9 ^b	529.7(.5)	677.9 ^a , 680.7 ^b	679.6(.5)		
3	4p ^e (3)	1s ^e	539.6 ^a , 537.1 ^b	537.5(.3)	691.7 ^a , 688.6 ^b	788.4(.8)		
						701 (1)		
						704 (1)		

* These energies were set equal to those of E. Holþien and S. Geltman [3].

^a E. Holþien and S. Geltman, Phys. Rev. 153, 81 (1967).

^b B. R. Junker and J. N. Bardsley, Phys. Rev. A8, 1345 (1973).

^c U. I. Safronova and V. N. Kharitonova, Opt. Spect. 27, 300 (1967).

^d Non-relativistic values corrected using relativistic correction of R. Snyder, J. Phys. B 4, 1150 (1971).

⁺ The parentheses following the experimental values contain the estimated error in eV.

Figure 3. Spectra of electrons from highly stripped F undergoing decay in flight, plotted in the rest frame of the emitting ion. The energy scale is established by assigning a value of 530.0 eV to the $4p^0(1)$ peak [3]. The continuous curve is drawn to aid the eye.

$3s^e$ and $3p^o$ series limits are also indicated in the figure.

The autoionization electron spectra of F is shown in Figure 3. The absolute energy scale was established by assigning the value of 530.0 eV [3] to the decay of the $4p^o(1)$ state in 3-electron F. Lines in the spectrum associated with the decay of core-excited states in 3-electron F are in many cases partially blended with contributions from similar transitions in 4- and 5-electron F. The latter transitions involve the 3-electron ion in excited states. The blending of similar lines makes it difficult to accurately measure the separation of the $3s^e$ and $3p^o$ series limits. Some of the possible states are indicated in Figure 1. The features of the F spectra are similar to those of the O spectra. The energies of the peaks measured in this experiment as well as some theoretically calculated energies are listed in Table I.

Figure 4. Spectrum of electrons from highly stripped Si, plotted in rest frame of emitting ion.

Figure 4 shows a prompt spectrum of electrons emitted from a 22.5 MeV foil-excited and highly stripped Si beam. In a similar delayed spectrum the small feature at 1303 eV became very prominent and can be associated with the $4p^0(1)$ metastable state in 3-electron Si. The observed energy agrees very well with three independent calculations [1,2,3]. The spectral feature at 1324 eV is probably a blend of the $4p^0(1)$ and $4p^1(1)$ states of 4- and 3-electron Si respectively. The feature around 1340 eV is a blend of lines associated with the decay of several possible autoionizing states: $2p^2(1)$, $3p^2(1)$ of 3-electron Si, $5p^2(1)$ of 4-electron Si and the $6s^0(1)$ of 5-electron Si. Other features remain unidentified at this time.

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- * Research supported in part by NSF Grant No. AST-75-10001 and the General Electric Corporation under contract W-31-109-ENG-41.
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