CONF-801111--56

L-SHELL IONIZATION IN HIGH-Z TARGETS BY CARBON AND SILICON IONS

P. Venugopala Rao

Department of Physics, Emory University, Atlanta, GA 30322

R. G. Albridge and A. V. Ramayya

Department of Physics, Vanderbilt University, Nashville, TN 37215†

M. C. Andrews, R. Mehta and F. D. McDaniel

Department of Physics, North Texas State University, Denton, TX 76203††

P. D. Miller

Oak Ridge National Laboratory, Oak Ridge, TN 37830*

MASTER

ABSTRACT

L-shell ionization in Ho, Er, Tm, Ta, W, Tl, Pb
and Bi by 20 MeV carbon ions and 37.5 MeV silicon ions
has been investigated. The observed L_{α}/L_{γ} x-ray
intensity ratios are compared with the estimates based
on PWBA and BEA calculations. The energy shifts in the
 L_{α} , L_{γ_1} and L_{γ_4} x rays are attributed to the presence
of M shell spectator vacancies.

DISCLAIMER

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Introduction

The present work is undertaken to investigate the relative importance of multiple vacancy production during the L-shell ionization by heavy charged particles. The most obvious effect of the spectator vacancies is to shift the energies of the L x ray lines. Such energy shifts have been observed in the past. Mokler¹ has shown that L x rays of both the colliding particles are shifted to higher energies in collisions between Iodine ions and Mo, Yb and Au targets and attributed the shifts to multiple ionization. Burkhalter et al.² have observed in the Ce L x ray spectra obtained by ⁴He ion bombardment a number of satellite lines due to the presence of additional M- and N-shell vacancies. Pepper et al.,³ who studied the L x ray production by ¹⁶O ions in Ce, Pr, Sm, Eu, Dy and Ho, reported energy shifts due to additional M-shell vacancies. On the other hand, Li et al.⁴ have observed no significant energy shifts or peak broadening in the L-x-ray spectra produced by ¹⁶O ions on Ta, Au, Bi and U targets. Energy shift measurements appear to be a useful method to determine the presence or absence of spectator vacancies at least in a qualitative way. However, most of the experimental studies are devoted to the measurement of the total or subshell ionization cross sections which are deduced from the observed L x ray intensities. The cross sections are related to the x-ray intensities through the fluorescence yields ω_i , Coster-Kronig transition probabilities f_{ij} and the x-ray emission rates F_{ij} in a well known way. Both experimental and theoretical values of ω_i , f_{ij} and F_{ij} are available for the single-vacancy atomic states over a wide range of atomic numbers. It is the normal practice to use these tabulated values of L-shell yields^{5,6} with the assumption that they are not significantly different for the multiply ionized states. This assumption is indeed harmless as long as the relative proportion of the multiple ionization is significantly small. When multiple ionization becomes comparable, the satellite structure in the L x ray spectra will become pronounced and the use of single-

*Supported by DOE under contract No. DE-A505-76ER05034

†Supported by Robert A. Welch Foundation, the Research Corporation & the North Texas State University Organized Research Fund. The acknowledgment is made to donors of the Petroleum Research Fund Administered by the American Chemical Society for partial support of this research.

*Partially supported by DOE, Division of Basic Sciences Contract No. W-7405-ENG-26 with Union Carbide Corp.

vacancy atomic state yields needs to be justified. The yields for the multiple-vacancy configurations have not been calculated and there are no experimental measurements of these rates except in some selected special cases of interest. Neither of these possibilities is likely to be realized in a systematic way because of the large variety of multiple-vacancy configurations that can be realized in any given experimental situation. However, an effort has to be initiated to develop useful techniques to study the effects of multiple ionization.

In the present work we report preliminary results on the energy shifts and L_{α}/L_{γ} intensity ratios in the L x ray spectra produced by carbon and silicon ions on heavy elements.

Experimental Procedures

20 MeV Carbon and 37.5 MeV silicon ions were obtained from the EN Tandem Van de Graaff accelerator at O.C.L. and bombarded solid foil targets of Ho, Er, Tm, Ta, W, Ti, Pb and Bi of various thicknesses. In some cases the targets were thick enough to be self-supporting while in other cases the very thin targets were vacuum deposited on thin carbon backings.

L-shell x-ray spectra were obtained from the above targets using a high-resolution 11" Applied Research Laboratories Curved-crystal x-ray spectrometer and a Si(Li) x-ray spectrometer mounted at 90° to the beam. Full width at half maximum energy resolutions at 8.14 keV were 169 eV and 155 eV respectively. All x-ray yields were normalized to the number of scattering ions detected in silicon surface barrier detectors.

The crystal spectrometer was used to study the L_{γ} region of the L x ray spectra of the lower-Z targets and to deduce the energies of their L_{γ_1} and L_{γ_2} lines. The intensities of L x rays for all the targets and the energies of L x rays from higher-Z targets are deduced from the spectra taken by Si(Li) detector. The response of these detectors in the energy region of interest is determined by taking K_{α} x ray spectra produced by bombarding targets of Fe, Cu, Zn, As, Rb and Ag. The absolute efficiency of the Si(Li) detector was determined using known standards of ^{59}Fe , ^{57}Co , ^{65}Zn , and ^{241}Am .

Results and Discussion

The energy shifts for the L_{α} x rays produced by 20 MeV carbon (4^+) ions are between 10 and 25 eV. For the L_{γ_1} x rays the shifts are between 40 and 60 eV. The shifts range from 90 to 200 eV for the L_{γ_2} x rays. In the case of 37.5 MeV Si(6^+) ions, the energy shifts are larger. The L_{α} x rays have shifts between 50 and 60 eV. The L_{γ_1} x ray energies are shifted to values between 200 and 230 eV while the L_{γ_4} energies have shifts between 400 and 500 eV.

We present in Table I average energy shifts for some prominent satellites. These are based upon

the calculations by M. H. Chen⁷ who used relaxed orbital Dirac-Hartree-Slater wavefunctions including QSD correction. The energy shift is defined as the difference between the energies of the satellite line and the diagram line. Only the range of shifts is given because the exact value depends upon the subshell location of the spectator vacancy.

It is obvious from a comparison of our preliminary results with the theoretical estimates, that there is more multiple ionization in the case of Si(6^+) ions. The presence of at least three spectator M vacancies is indicated. The carbon projectile data can be explained by assuming only one M vacancy.

The L_{α}/L_{γ} intensity ratios are presented in Table II along with estimates based upon the theoretical PWBA and BEA calculations. These estimates are obtained using the single-vacancy atomic yields recently compiled by Krause et al.⁶ The experimental ratios have uncertainties of about 5% primarily due to the errors arising in the efficiency calibration of the detector.

The motivation for paying special attention to the L_{α}/L_{γ} intensity ratios is the following. The L_{α} x rays arise from the decay to L_3 -vacancy states. The L_3 -vacancy states are produced by two different mechanisms. There are those created primarily through the projectile-target interaction and those that are transferred from L_1 and L_2 subshells due to Coster-Kronig transitions. Thus the observed L_{α}/L_{γ} x ray intensity ratio must reflect any changes that take place in the L_1 and L_2 Coster-Kronig transition probabilities. In particular the L_1 subshell Coster-Kronig transition probability makes a sharp jump after $Z = 74$ because of the availability of sufficient energy to eject M_4 or M_5 electrons. For example, the f_{13} has a value of about 0.3 from $Z = 50$ to $Z = 74$ and increases quickly to a value of 0.6 at $Z = 80$.

Table I. Average energy shifts (ΔE in eV) for the satellites of L_{α} and L_{γ_1} x rays

Z	Spectator vacancy	$(\Delta E)_{L_{\alpha}}$	$(\Delta E)_{L_{\gamma_1}}$
67 Ho	M	16-20	47-55
	N	1-2.5	5-7
70 Yb	M	18-26	50-60
	N	2-4	5-9
74 W	M	20-29	55-64
	N	2-4	6-11
78 Pt	M	21-28	61-69
	N	2-4	8-13

Table II. L_{α}/L_{γ} x-ray intensity ratios

Z	20 MeV C^{5+}			37.5 MeV $Si(6^+)$			target thickness
	Expt.	PWBA	BEA	Expt.	PWBA	BEA	
67 Ho	9.7	12.3	13.1	13.8	13.5	13.1	142 $\mu g/cm^2$
68 Er	12.1	12.6	13.2	13.1	13.7	14.0	6.5 mg/cm^2
69 Tm	12.5	13.1	13.6	13.3	13.9	12.9	25 mg/cm^2
73 Ta	11.5	13.7	13.3	11.7	14.7	12.8	1.97 mg/cm^2
74 W	12.1	13.9	13.2	11.6	14.9	12.8	1.4 mg/cm^2
81 Te	11.4	17.3	15.8	11.4	18.2	15.1	100 $\mu g/cm^2$
82 Pb	11.4	17.6	16.0	10.7	18.4	15.3	100 $\mu g/cm^2$
83 Bi	12.6	18.2	15.9	10.7	18.6	15.3	80 $\mu g/cm^2$

Acknowledgement

The authors acknowledge the travel support provided by ORAU.

The results of the work indicate that there is general agreement between theory and experiment except that at high Z the theoretical estimates are high. Assuming that multiple ionization plays no substantial role and the use of single vacancy atomic yields σ_i and f_{i1} is justified, we can conclude that the theory predicts relatively more ionization in L_3 subshell than in L_1 and L_2 subshells. It is also possible that multiple ionization can give rise to small changes in the L_1 subshell Coster-Kronig and x-ray yields which can account for this discrepancy. To investigate such a possibility of changes in Coster-Kronig yields, one should actually create experimental conditions in which L_1 subshell ionization has a much larger probability to start with. In the present situation only about 5% of the primary ionization takes place in the L_1 subshell. Experiments in which larger amount of multiple ionization is present are in progress. A more detailed analysis of the present data will be presented elsewhere.

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