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L-Shell X-Ray Production Cross Sections in Nd, Gd, Ho, Yb, Au and Pb for
25-MeV Carbon and 32-MeV Oxygen Ions*

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Abstract

L-shell x-ray production cross sections in ^{60}Nd , ^{64}Gd , ^{67}Ho , ^{70}Yb , ^{79}Au and ^{82}Pb have been measured for incident 25 MeV $^{12}_6\text{C}^{+q}$ ($q=4,5,6$) and 32 MeV $^{16}_8\text{O}^{+q}$ ($q=5,7,8$) ions. Measurements were made on targets ranging in thickness from 1 to 100 $\mu\text{g}/\text{cm}^2$. Enhancement in the L-shell x-ray production cross section for projectiles with one or two K-shell vacancies over those for projectiles with no K-shell vacancies is observed. The sum of direct ionization to the continuum (DI) plus electron capture (EC) to the L,M,N... shells and EC to the K-shell of the projectile have been extracted from the data. Calculations in the first Born approximation are 10 times larger than the data. Predictions of the ECPSSR theory that accounts for for the energy-loss, Coulomb deflection, perturbed-stationary state, and relativistic effects are in good agreement with the data for both ions.

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Introduction

The strong effects of projectile charge state on inner-shell ionization have been reported by a number of groups for gas targets.¹⁻⁴ The large increases in target ionization for projectiles with K-vacancies over those without K-vacancies were explained by Halpern and Law⁵ as electron transfer from the target K shell to the projectile K shell.

For solid targets, the particular electron configuration of the ion while inside the target is not well understood.⁶ The effects of residual K-shell vacancies in the projectile on solid target x-ray production have been reported by Hopkins⁷ and Groeneveld et al.⁸ Precise measurements of solid target K-shell x-ray production as a function of target thickness have been made for projectiles with and without K-shell vacancies by Gray et al.⁹ and McDaniel et al.¹⁰ Both groups found the variation in target x-ray production with target thickness could be explained in terms of the number of K-vacancies in the projectile. For projectiles with K-vacancies, ionization in the target could be produced by K to K electron capture (EC) from the target atom to the projectile as well as direct ionization (DI) of the target and electron capture to the L-, M-, ... shells of the projectile. For projectiles without K-vacancies, only direct ionization and electron capture to the L-, M-, ... shells of the projectile are possible.

McDaniel et al.¹¹ also measured the projectile charge state dependence of target L-shell x-ray production for ^{60}Nd , ^{67}Ho , and ^{79}Au for 1.86 MeV/amu ^{19}F and $^{28}_{14}\text{Si}$ and 1.8 MeV/amu $^{35}_{17}\text{Cl}$ ions as a function of target thickness. The data were explained in terms of direct ionization and electron capture contributions to inner-shell ionization.

Mehta et al.¹² have recently made measurements of M-shell x-ray production for ^{79}Au , ^{82}Pb , ^{83}Bi , and ^{92}U for ^{19}F ion bombardment as a function of target thickness and ^{19}F charge state. Target M-shell x-ray production for projectiles with a K-vacancy were enhanced over that for projectiles without a K-vacancy.

The present work was undertaken to expand these investigations to somewhat lighter projectiles of comparable speed. L-shell x-ray production cross sections have been measured for 25 MeV $^{12}\text{C}^{+q}$ ($q = 4, 5, 6,$) and 32 MeV $^{16}\text{O}^{+q}$ ($q=5, 7, 8$) ions incident on targets of ^{60}Nd , ^{64}Zn , ^{67}Zn , ^{70}Yb , ^{79}Au , and ^{82}Pb of thicknesses from $\sim 1 - 100 \mu\text{g}/\text{cm}^2$. The L-shell x-ray cross sections for electron capture to the K-shell of the ion and the sum of direct ionization and electron capture to the L-, M-,... shells of the ion were extracted from the data for the thinnest targets, which approximate single collision conditions, by subtracting the target M-shell x-ray cross sections for ions with no K-vacancies from those with one- or two-K-vacancies.

Theoretical models available to explain these processes include the first Born approximation and the ECPSSR theory. The plane-wave Born approximation (PWBA)¹³ is employed for DI and the Oppenheimer-Brinkman-Kramers approximation of Nikolaev (OBKN)¹⁴ is used for EC. The ECPSSR¹⁵ theory that goes beyond the first Born approximation and accounts for energy loss (E), Coulomb deflection (C), and relativistic effects (R) in the perturbed stationary state approach is tested for both DI and EC. These perturbative theories are expected to be better for lighter projectiles (^{6}C and ^{9}O of this work vs. ^{9}F and ^{14}Si , and ^{17}Cl of Ref. 11). Yet, the collision systems chosen in this work have sufficiently large Z_1/Z_2 ratios so that electron capture may significantly contribute to the x-ray production enhancement.

Experimental Procedure and Data Analysis

Ion beams of 25 MeV carbon and 32 MeV oxygen were obtained from the 6.5 MV EN Tandem Van de Graaff accelerator at the Oak Ridge National Laboratory. The charge states q of the ions were $q=4,5,6$ for $^{12}_{6}\text{C}^{+q}$ and $q=5,7,8$ for $^{16}_{8}\text{O}^{+q}$ ions. The collimated ion beam was incident on the solid targets positioned at 45° to the incident beam direction. The x-rays produced in the target were measured by an ORTEC Si(Li) detector positioned at 90° with respect to the beam direction. The scattered particles were detected by a silicon surface barrier detector at 45° with respect to the incident beam.

L-shell x-rays were measured for targets ranging in thickness from 1 to $100 \mu\text{g}/\text{cm}^2$. The targets were prepared by vacuum deposition of each element on 10 to $15 \mu\text{g}/\text{cm}^2$ ultra clean carbon backings. The carbon backings were screened to make sure there was minimal presence of low Z contaminants. Details for making contaminant-free targets are given in Reference 16. L-shell x-ray production cross sections were determined by normalizing the x-ray yield to the Rutherford yield of the scattered particles. Particulars of the experimental geometry and data analysis have been discussed in Reference 17,

The efficiency of the Si(Li) detector was determined (A) by measuring the x-rays emitted from calibrated sources of ^{57}Co , ^{65}Zn and ^{241}Am and (B) by measuring the K-shell x-ray yields per scattered particle from thin targets of ^{11}Na , ^{14}Si , ^{16}S , ^{17}Cl and ^{30}Zn for incident $^{12}_{6}\text{C}^{+4}$, $^{16}_{8}\text{O}^{+5}$ and $^{19}_{9}\text{F}^{+4}$ ion beams and dividing them by available experimental K-shell x-ray production cross sections in Reference 18 and (C) calculating the attenuation of the x-rays in the Mylar film, Be entrance window, Au contact

layer and the Si dead layer, and normalizing the theoretical curve determined from the above attenuation calculations to a measured efficiency point at a higher X-ray energy. The normalized curve was used in the determination of the cross section values.

Table 1 presents the measured L-shell X-ray production cross sections for 25 MeV carbon and 32 MeV oxygen ions in various charge states. The absolute errors in the cross section measurements range from 13.7% to 18.5% with the largest contribution coming from background subtraction (1-10%) and efficiency measurements (10-14%). The relative errors in the cross section measurements range from 3-11%.

Results and Discussion

The L-shell x-ray production cross sections were determined from the weighted average cross section for the thinnest (~ 1 to $3 \mu\text{g}/\text{cm}^2$) targets which represent approximately single collision conditions. The L-shell to K-shell EC cross sections are inferred by subtracting the target L-shell x-ray production cross sections by the projectile with no K-shell vacancies from the target L-shell x-ray production cross sections by projectiles with one or two K-shell vacancies. For the sake of comparison the L-shell ionization cross section predictions by the first Born and ECPSSR theories are converted to the L-shell x-ray production cross section using the single-hole fluorescence yields and the Coster-Kronig transition rates from Krause.¹⁹

In Figure 1, the measured target L-shell x-ray production cross section σ_{XL} for incident $^{12}_{6}\text{C}^{+q}$ and $^{16}_{8}\text{O}^{+q}$ ions are shown versus Z_1/Z_2 , where Z_1 and Z_2 are the atomic numbers of the projectile and the target, respectively. A solid circle, a half-filled circle and an open circle denote measurements made with ions with zero, one or two K-shell vacancies, respectively. The solid circles, representing the helium like ($q=Z_1-2$) ions, are found to have a constant value for the range of thicknesses used for each target in these measurements. The one and two K-shell vacancies occur in hydrogen-like ($q=Z_1-1$) and fully stripped ($q=Z_1$) carbon or oxygen ions. The predictions of the ECPSSR theory are shown as a solid curve, with the upper of the three curves for ions with two K-shell vacancies, the middle one for one K-shell vacancy and the bottom for ions with no K-shell vacancy. Comparison among the three σ_{XL} cross sections shown here for the same ion-target combination indicates an enhancement in σ_{XL} for measurements made with ions with K-shell vacancies over those without any K-shell vacancies. Also, the increase in σ_{XL} is larger for ions with two K-shell vacancies than those

with one K-shell vacancy. In addition, these enhancements for a particular ion increase with decreasing Z_2 .

The inferred target L-shell to projectile K-shell EC cross sections for ^{60}Nd , ^{64}Gd , ^{67}Ho , ^{70}Yb , ^{79}Au , and ^{82}Pb for hydrogen-like ($q=Z_1-1$) and fully stripped ($q=Z_1$) carbon and oxygen ions, are plotted in Figures 2 and 3, respectively, versus Z_1/Z_2 . The ratio of projectile velocity v_1 to L-shell electron orbital velocity v_{2L} is given by $v_1/v_{2L} = (n^2 E_1 / \lambda Z_2^2 R)^{0.5}$. Here E_1 is the projectile energy, λ is the ratio of projectile mass to the electron mass, n is the principal quantum number ($n=2$ for L-shell), $R=13.6$ eV is the Rydberg constant and $Z_{2L}=Z_2^{-4.15}$. For the 25-MeV carbon ions the value of v_1/v_{2L} ranged from 0.33 (Nd) to 0.23 (Pb) while for the oxygen ions they ranged from 0.32 (Nd) to 0.23 (Pb), as these projectiles have nearly the same speed.

The predictions of the first Born approximation and the ECPSSR theories are shown by broken and solid curves, respectively. The first Born approximation overpredicts the data by a factor of 10. The slopes and the magnitudes of the ECPSSR calculations and the measured data are in good agreement.

In conclusion, L-shell x-ray production cross sections were measured for incident 25 MeV $^{12}\text{C}^{+q}$ ($q=4,5,6$) and 32 MeV $^{16}\text{O}^{+q}$ ($q=5,7,8$) ions on targets of Nd, Gd, Ho, Yb, Au, and Pb. The cross sections are seen to be enhanced for highly stripped projectiles which carry a K-shell vacancy with them into the collision. This is attributed to the formation of the target L-shell vacancies via the electron capture from the L-shell of the target into the K-shell of the projectile. On the average the enhancement is seen to be twice as much for the case of ions with 2 K-shell vacancies over those with 1 K-shell vacancy. Also, for the same number of K-shell vacancies and nearly the same projectile velocity, the enhancement is larger for the higher Z_1 projectile. Excellent agreement between the ECPSSR theory and the inferred EC cross section was found.

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TABLE I. Measured L-shell X-ray Production Cross Sections (barns)

Target	25 MeV $^{12}_6\text{C}^{+q}$			32 MeV $^{16}_8\text{O}^{+q}$		
	q=4	q=5	q=6	q=5	q=7	q=8
^{60}Nd	5050 +790	5500 +870	5980 +930	6890 +1290	8530 +1410	10200 +1660
^{64}Gd	3840 +650	4150 +700	4420 +750	5490 +800	6970 +970	7590 +1060
^{67}Ho	2650 +450	2850 +480	3030 +510	3940 +540	4790 +670	5530 +810
^{70}Yb	2020 +300	2150 +320	2260 +330	2760 +380	3190 +440	3490 +490
^{79}Au	876 +136	931 +144	966 +150	1250 +230	1430 +260	1410 +260
^{82}Pb	749 +135	779 +139	801 +144	869 +138	928 +148	1020 +160

Figure 1.

Measured L-shell x-ray production cross section σ_{XL} versus Z_2 and Z_1/Z_2 . The two projectiles used were $^{12}_{6}\text{C}^{+q}$ and $^{16}_{8}\text{O}^{+q}$ and had nearly the same speed. The carbon data for $q=4,5,6$ are on the left side of the graph while the oxygen data for $q=5,7,8$ are on the right. The atomic symbol of the target (Z_2) is shown for easy identification. The curves represent the predictions of the ECPSSR theory of Reference 15. Two sets of three solid curves for each ion are drawn. In each set the upper, middle and the bottom curves are the ECPSSR calculations of the target σ_{XL} cross section for an ion with 2, 1 and no K-shell vacancies, respectively.

Figure 2.

The inferred target (Z_2) L-shell to projectile K-shell x-ray production cross section due to electron capture $\sigma_{XL}^{EC(L \rightarrow \frac{1}{2}K)}$ for 1 K-shell vacancy ($q=5$ for $^{12}_6C^{q+}$ and $q=7$ for $^{16}_8O^{q+}$) present in the projectile versus Z_1/Z_2 . The energies of the incident carbon and oxygen ions were 25 and 32 MeV, respectively.

Figure 3.

The inferred target (Z_2) L-shell to projectile K-shell x-ray production cross section due to electron capture $\sigma_{XL}^{EC(L \rightarrow K)}$ for 2 K-shell vacancies ($q=6$ for $^{12}_{6}\text{C}^{+q}$ and $q=8$ for $^{16}_{8}\text{O}^{+q}$) present in the projectile versus Z_1/Z_2 . The energies of the incident carbon and oxygen ions were 25 and 35 MeV, respectively.