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Study of the L-shell x-ray production cross section of cadmium by proton bombardment

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The L-shell x-ray production process in cadmium for proton bombardment over the energy range 120 – 420 keV was studied using thin Cd targets ($\sim 30\ \mu g/cm^2$). The x rays were observed with a high-purity Ge low-energy-photon-spectroscopy detector. The total x-ray cross sections were determined at 20-keV intervals in the bombarding energy range. Experimental cross sections were compared to the predictions of the nonrelativistic plane-wave Born approximation and the perturbed stationary-state theory with relativistic and Coulomb deflection corrections (CPSSR). The total L-shell x-ray cross sections are in reasonable agreement with the CPSSR theory. The complex L x-ray spectrum was resolved into several components and the relative x-ray cross sections of these components were determined.

INTRODUCTION

In the high-speed collision between a bombarding ion and a target atom, the Coulomb interaction can result in the ionization of the target atom and lead to the emission of characteristic x rays or Auger electrons. A competing process which also leads to ionization of the target atom is electron capture by the bombarding ion. Recently the study of characteristic x-ray production by ion bombardment has resulted in measurements of K- and L-shell x-ray cross sections for many target elements and for several bombarding ions.[1] From these experimental results and the theoretical advances that have been made to account for the results, an improved understanding of inner-shell atomic processes is emerging. In addition, the cross-section results have been very useful for those studies of proton-induced x-ray emission (PIXE) as a method of trace element analysis.

The experimental work to date has been abundant for bombarding energies greater than 500 keV, especially for light bombarding ions (protons, deuterons, and alpha particles). At bombarding energies below 500 keV comparatively few elements have been studied.[2] There is merit in extending these measurements to lower bombarding energies, both to test the present theoretical descriptions and to see if the ionization process depends upon the energy in subtle ways that have not yet been anticipated.

Several theories have been used to describe the ejection of inner-shell electrons due to charged particle bombardment. The nonrelativistic plane-wave Born approximation (PWBA)[3] has provided a satisfactory description especially for light ions at higher bombarding energies, but it cannot be precisely correct, particularly at low energy, because it neglects (1) the perturbation of the target atom by the projectile as it passes through the atom, (2) the deflection of the projectile by the Coulomb field of the nucleus, and (3) the relativistic motion of the inner-shell electrons. Each of these features has been incorporated as a modification of the basic PWBA approach, and the resulting theory is called the perturbed stationary state (PSS) with Coulomb (C) and relativistic (R) corrections (CPSSR).[4,5] The CPSSR theory is in substantial agreement with most of the available data, and is expected to agree with the experimental results of this investigation. For proton bombardment at these low energies, electron capture is not expected to contribute to the ionization process.

EXPERIMENTAL PROCEDURE AND APPARATUS

The beam of protons from the AN-400 Van de Graaff accelerator at Mankato State University was magnetically analyzed and slit stabilized. In the target chamber the beam passed through a carbon collimator, through the cadmium target placed at a 45° angle to the beam, and into a Faraday cup. A HPGe LEPS (high-purity Ge low-energy-photon-spectroscopy) detector with a 6-mm active diameter and a resolution of 151-eV FWHM at 5.9 keV was mounted at 90° to the beam and located outside the vacuum system directly below the target.

Targets were prepared by vacuum evaporation of 99.9% pure cadmium pellets placed on a tantalum boat. The cadmium was evaporated onto a thin ($\sim 30\ \mu g/cm^2$) foil of 99.9995% pure carbon and mounted on a 4-cm by 6-cm aluminum target holder with a 1-cm diameter hole. The target thickness was determined by the Rutherford scattering of protons into surface barrier detectors at an angle of approximately 135°. Two targets were analyzed both before and after all x-ray runs to verify that there was no depletion of target material. The mass thicknesses of the two targets were determined to be 31.6 $\mu g/cm^2$ and 25.7 $\mu g/cm^2$ to an accuracy of about 6%.

The energy of the Van de Graaff accelerator was calibrated to an accuracy of 2% using the resonance reaction $^{19}F(p, \alpha\gamma)^{16}O$ that occurs at 340 keV. An ^{241}Am source, obtained from New England Nuclear and possessing an activity certified to 3.4%, was used for the energy calibration and efficiency determination of the HPGe detector. The source was placed in the target position and the photon spectrum was obtained. The intensities of the Np $L\alpha$ and M x rays were compared, taking into consideration (a) the absorption in the Be windows of the detector and target chamber (thicknesses of 0.127 and 0.028 mm, respectively) and intervening air (path length of 15 ± 1 mm), (b) the ratios of photons per decay[6] (0.0635 ± 0.0060 for the M x rays and 0.135 ± 0.003 for the $L\alpha$ x rays), and (c) the escape of germanium K x rays in the case of the $L\alpha$ x rays. The $L\alpha$ and M x-ray intensities were consistent, within the uncertainty in the ratios of photons per decay. The average detection efficiency of $(9.9 \pm 1.0) \times 10^{-5}$ over the energy interval of the complex L-shell x-ray spectrum of cadmium was calculated from the measured efficiency of the Np M x rays, taking account of the absorption in the Be windows and intervening air.

RESULTS

A typical L x-ray spectrum of cadmium is shown in Fig. 1 for a proton bombarding energy of 420 keV. The complex structure of the spectrum is apparent, but for determining the total L x-ray production cross section it was unnecessary to resolve this spectrum into its components. Two separate cadmium targets were analyzed for bombarding energies of 120 to 420 keV in steps of 20 keV. The average total L x-ray cross section for each energy is given in Table I and Fig. 2. Also

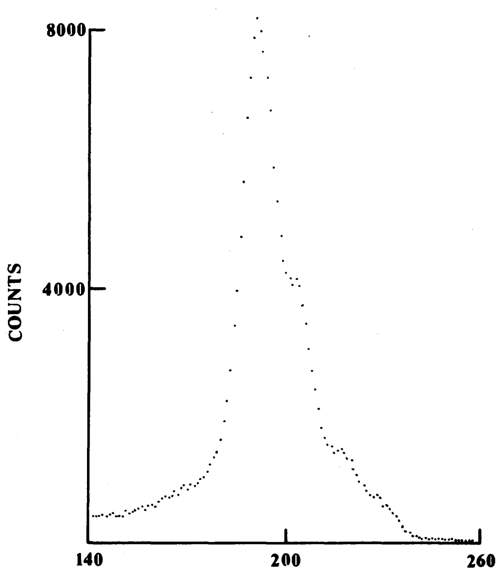

FIG. 1. Cadmium L-shell x-ray spectrum at a proton energy of 420 keV.

TABLE I. Total L-shell x-ray production cross sections of cadmium.

Proton energy (keV)	Experimental: Average (*b*)	Experimental: Other Work[a] (*b*)	Theoretical: CPSSR (*b*)	Theoretical: PWBA (*b*)
420	19.4 ± 2.9		26.8	41.2
400	17.6 ± 2.6	4.50	23.5	37.1
380	15.3 ± 2.3		20.5	33.1
360	13.2 ± 2.0		17.7	29.4
340	11.2 ± 1.7		15.2	25.9
320	9.2 ± 1.4		12.6	22.3
300	7.4 ± 1.1	2.20	10.4	19.1
280	6.18 ± 0.99		8.47	16.2
260	5.13 ± 0.82		6.73	13.6
240	4.11 ± 0.66		5.24	11.2
220	2.93 ± 0.47		3.90	8.84
200	2.06 ± 0.33	0.980	2.76	6.88
180	1.49 ± 0.24		1.87	5.20
160	0.83 ± 0.14		1.17	3.65
140	0.528 ± 0.090		0.633	2.41
120	0.262 ± 0.045		0.299	1.49

[a] R. C. Jopson, H. Mark, and C. D. Swift, Phys. Rev. 127, 1612 (1962).

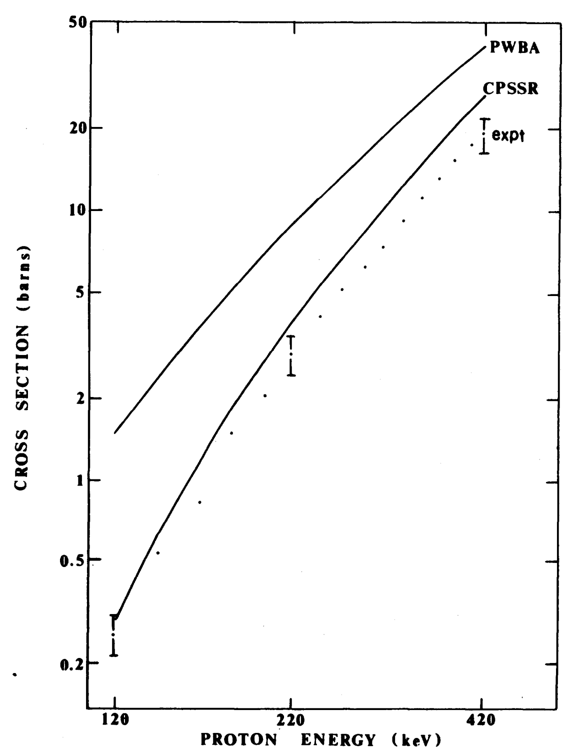

FIG. 2. Cadmium total L-shell x-ray production cross sections versus proton energy.

TABLE II. Relative x-ray intensities for 220-keV and 420-keV protons on cadmium.

Transition	Relative intensity corrected for absorption 220 keV	420 keV
$L\alpha_{1,2}$	1.000	1.000
$L\beta_{1,3,4,6}$	0.308 ± 0.033	0.327 ± 0.033
$L\beta_{2,15}$	0.113 ± 0.015	0.125 ± 0.015
$L\gamma_1$	0.040 ± 0.006	0.033 ± 0.005
$L\gamma_2$		0.0014 ± 0.0004

presented are theoretical predictions based upon the PWBA and CPSSR theories. The total L x-ray cross section σ_x can be expressed in terms of the theoretical subshell ionization cross sections by the following:

$$\sigma_x = \nu_{\rm I}\,\sigma_{L_{\rm I}} + \nu_{\rm II}\,\sigma_{L_{\rm II}} + \nu_{\rm III}\,\sigma_{L_{\rm III}} ,$$

where the σ_L's are the subshell ionization cross sections. The ν's are related to the subshell fluorescence yields (ω_i's) and the Coster-Kronig transition probabilities (f_{ij}'s) by the following:

$$\nu_{\rm I} = \omega_1 + \omega_2 f_{12} + \omega_3 (f_{13} + f_{12} f_{23}) ,$$

$$\nu_{\rm II} = \omega_2 + \omega_3 f_{23} ,$$

$$\nu_{\rm III} = \omega_3 .$$

The values of these quantities were taken from a compilation by Krause[7] and are

$$\omega_1 = 0.018 , \quad f_{12} = 0.10 ,$$

$$\omega_2 = 0.056 , \quad f_{13} = 0.59 ,$$

$$\omega_3 = 0.056 , \quad f_{23} = 0.155 .$$

The total L x ray cross section for cadmium is then

$$\sigma_x = (0.058)\sigma_{L_{\rm I}} + (0.065)\sigma_{L_{\rm II}} + (0.056)\sigma_{L_{\rm III}} .$$

The subshell ionization cross sections were computed from the PWBA (Ref. 3) and CPSSR (Ref. 5) theories using the subshell ionization energies[8] $U_{\rm I} = 4018.0$ eV, $U_{\rm II} = 3727.0$ eV, and $U_{\rm III} = 3537.5$ eV. As expected, the CPSSR theory is in reasonable agreement with the experimental results.

Additional information is present in the complex L x ray spectrum of Fig. 1, and can be used to test details of the theoretical models. For bombarding energies of 420 and 220 keV the spectrum was separated into its components by fitting a series of Gaussian curves to the photopeaks. Each component was associated with a particular x-ray transition or group of unresolved transitions. The intensity of each component, corrected for x-ray absorption in Be windows and intervening air, was determined relative to the dominant component, whose intensity was set equal to unity. These relative intensities, given in Table II, are immune to several uncertainties that affect the absolute cross-section results. At 220 keV the $L\gamma_2$ x ray was not observed.

Four of the five observed photopeaks consist of transitions in which the final state is one of the three L subshell energy levels. For these four we may write the cross sections as follows:

$$\sigma_{L\alpha_{12}} = [\sigma_{L_{\rm III}} + f_{23}\sigma_{L_{\rm II}} + (f_{13} + f_{12} f_{23})\sigma_{L_{\rm I}}] \times \omega_3 \frac{\Gamma_{3\alpha_1} + \Gamma_{3\alpha_2}}{\Gamma_3} ,$$

$$\sigma_{L\beta_{2,15}} = [\sigma_{L_{\rm III}} + f_{23}\sigma_{L_{\rm II}} + (f_{13} + f_{12} f_{23})\sigma_{L_{\rm I}}] \times \omega_3 \frac{\Gamma_{3\beta_2} + \Gamma_{3\beta_{15}}}{\Gamma_3} ,$$

$$\sigma_{L\gamma_1} = (\sigma_{L_{\rm II}} + f_{12}\sigma_{L_{\rm I}})\omega_2 \frac{\Gamma_{2\gamma_1}}{\Gamma_2} ,$$

$$\sigma_{L\gamma_2} = \sigma_{L_{\rm I}}\omega_1 \frac{\Gamma_{1\gamma_2}}{\Gamma_1} ,$$

TABLE III. Relative x-ray intensity ratios for 220-keV and 420-keV protons on cadmium.

Proton energy (keV)	Ratio	CPSSR	PWBA	Experimental
420	$L\alpha/L\beta_{2,15}$	9.80	9.80	8.0 ± 0.8
	$L\alpha/L\gamma_1$	25.8	27.6	30 ± 5
	$L\alpha/L\gamma_2$	660	693	710 ± 200
	$L\gamma_1/L\gamma_2$	25.6	25.1	24 ± 7
	$L\beta_{2,15}/L\gamma_1$	2.64	2.82	3.8 ± 0.7
	$L\beta_{2,15}/L\gamma_2$	67.4	70.8	89 ± 25
220	$L\alpha/L\beta_{2,15}$	10.5	9.80	8.8 ± 0.9
	$L\alpha/L\gamma_1$	28.0	29.6	26 ± 4
	$L\alpha/L\gamma_2$	260	333	
	$L\gamma_1/L\gamma_2$	9.28	11.2	
	$L\beta_{2,15}/L\gamma_1$	2.67	3.02	2.9 ± 0.6
	$L\beta_{2,15}/L\gamma_2$	24.8	34.0	

where the Γ's are radiative widths taken from Scofield's work.[9] Ratios of experimental intensities and theoretical cross sections are compared in Table III.

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