X-Ray Production in the L Shell of Copper by 25- to 1700-eV Protons*

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L-shell x rays of copper were produced by stopping 25- to 1700-keV protons in a thick target. X rays associated with the production of initial vacancies in the L_{III} shell were isolated by an absorption technique. Total L-shell x-ray yield is presented, as well as yield, production, and ionization cross sections for the L_{III} shell. The Born approximation is compared with the experimental ionization cross section and is found to be consistently high over the whole range of bombarding energies.

INTRODUCTION

The present work is an extension of the systematic study of inner-shell ionization by proton bombardment.[1–3] The principal motivation is the testing of the currently available model describing this class of inelastic scattering processes. The two models existing at the present time may be termed the Born approximation[1] (plane-wave proton description) and the semiclassical deflected-proton-trajectory model of Bang and Hansteen.[4] Of the two, calculated values for the L_{III} shell are available only for the Born approximation.

The experimental technique employed utilized the L_{III} absorption edge of copper (i.e., 933 eV) to selectively attenuate L-shell x rays of energy greater than the L_{III} edge.[2b] It is assumed that L-shell radiation resulting from multiple initial ionizations and Coster-Kronig processes has energy greater than the L_{III} edge. Under this assumption, and further that the L_{III}-shell vacancies are filled principally by electrons originating in the M_4, M_5 and conduction band, it is interpreted that the transmitted component (L_α) may be employed to obtain the x-ray production and ionization cross sections for the L_{III} shell of copper.

Table I. Copper L_{III}-shell yield and ionization cross section.

E_p (keV)	I^0 [a] x rays / proton	I_α^0 [b]	$\frac{dI_\alpha^0}{dE}$	$S(E)$[c]	$\frac{1}{n}\frac{dI_\alpha^0}{dE}S(E)$	$\frac{1}{n}\frac{\mu}{\rho}I_\alpha^0$	σ_x	$\sigma_I=\frac{\sigma_x}{\omega_L}$ [d]
26	5.2 (−8)	2.27(−8)	8.2(−9)	125	1.1(−25)	4.3(−27)	1.1(−25)	2.3(−24)
31	2.04(−7)	9.49(−8)	2.4(−8)	150	3.8(−25)	1.8(−26)	4.0(−25)	8.0(−24)
41	1.04(−6)	5.38(−7)	7.5(−8)	170	1.3(−24)	9.5(−26)	1.4(−25)	2.9(−23)
51	2.96(−6)	1.53(−6)	1.4(−7)	190	2.8(−24)	2.7(−25)	3.1(−24)	6.1(−23)
61	6.13(−6)	3.26(−6)	2.3(−7)	200	4.9(−24)	5.7(−25)	5.4(−24)	1.1(−22)
71	1.09(−5)	5.96(−6)	3.2(−7)	210	7.1(−24)	1.1(−24)	8.1(−24)	1.6(−22)
81	1.76(−5)	9.45(−6)	4.3(−7)	215	9.8(−24)	1.7(−24)	1 2(−23)	2.3(−22)
91	2.59(−5)	1.45(−5)	5.7(−7)	220	1.3(−23)	2.5(−24)	1.6(−23)	3.0(−22)
100	3.76(−5)	2.10(−5)	6.1(−7)	225	1.5(−23)	3.4(−24)	1.8(−23)	3.6(−22)
200	[2.96(−4)]	[1.75(−4)]						[1.5(−21)] [e]
300	[8.61(−4)]	[5.20(−4)]						[3.4(−21)] [e]
400	[1.61(−3)]	[1.01(−3)]						[5.5(−21)] [e]
500	2.54(−3)	1.62(−3)	6.2(−6)	170	1.1(−22)	2.8(−22)	3.9(−22)	7.8(−21)
600	3.54(−3)	2.31(−3)	7.1(−6)	157	1.2(−22)	4.0(−22)	5.2(−22)	1.0(−20)
700	4.52(−3)	3.02(−3)	6.9(−6)	147	1.1(−22)	5.2(−22)	6.3(−22)	1.3(−20)
800	5.43(−3)	3.68(−3)	6.0(−6)	138	8.8(−23)	6.2(−22)	7.1(−22)	1.4(−20)
900	6.40(−3)	4.34(−3)	5.8(−6)	130	8.0(−23)	7.2(−22)	8.0(−22)	1.6(−20)
1000	7.21(−3)	4.96(−3)	5.7(−6)	124	7.5(−23)	8.3(−22)	9.0(−22)	1.8(−20)
1100	7.96(−3)	5.57(−3)	5.0(−6)	117	6.2(−23)	9.1(−22)	9.7(−22)	1.9(−20)
1200	8.61(−3)	6.19(−3)	5.0(−6)	111	5.8(−23)	1.0(−21)	1.1(−21)	2.3(−20)
1300	9.26(−3)	6.77(−3)	4.6(−6)	105	5.1(−23)	1.1(−21)	1.1(−21)	2.4(−20)
1400	9.74(−3)	7.36(−3)	3.9(−6)	100	4.1(−23)	1.2(−21)	1.2(−21)	2.4(−20)
1500	1.02(−2)	7.82(−3)	3.4(−6)	96	3.5(−23)	1.2(−21)	1.3(−21)	2.6(−20)
1600	1.05(−2)	8.36(−3)	3.1(−6)	90	3.0(−23)	1.3(−21)	1.3(−21)	2.6(−20)
1700	1.09(−2)	8.90(−3)	3.0(−6)	86	2.7(−23)	1.4(−21)	1.4(−21)	2.8(−20)

[a] 1. I[x rays/protons] $=N(E)$[counts/charge collected] $\times(1/T_wA_c)\times4\pi R^2/(\text{area})_c$; T_w = counter-window transmission; A_c = counter absorption; R = window to target distance; $(\text{area})_c$ = counter-window area. 2. Estimated limits of error ±15%.
[b] Estimated limits of error ±20%.
[c] S. D. Warshaw and S. K. Allison, Rev. Mod. Phys. 25, 779 (1953).
[d] ω_L estimated at 0.05.
[e] Interpolated-curve values.

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[1] For a general review of subject, see E. Merzbacher and H. W. Lewis, in *Handbook of Physics*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 166.
[2] (a) J. M. Khan and D. L. Potter, Phys. Rev. 133, A890 (1964); (b) J. M. Khan, D. L. Potter, and R. D. Worley, *ibid.* 134, A316 (1964); (c) 135, A511 (1964); (d) 136, A108 (1964).
[3] J. M. Khan, D. L. Potter, and R. D. Worley, Phys. Rev. 139, A1735 (1965).
[4] J. Bang and J. M. Hansteen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 31, No. 13 (1959).

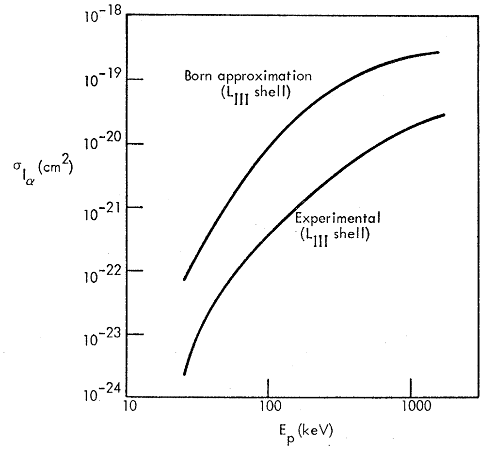

FIG. 1. Copper L_{III} ionization cross section.

MEASUREMENTS

The apparatus, method and calculational procedure have appeared in print previously and will not be reproduced in detail.[2,3] It is useful, however, to review the experiment for purposes of gaining perspective.

A magnetically analyzed beam of protons was supplied by each of two accelerator systems covering the energy ranges 0–100 keV and 500–1700 keV. The latter system was a van de Graaff accelerator. The beam of protons entered a separately pumped target chamber after suitable collimation. The target samples were mounted at 45° to the beam on a solid aluminum rod. X rays produced at the target were observed at 90° to the beam direction. After passing through an absorber foil changer, the x rays were detected by a thin window (e.g., 0.27-mil Al) proportional counter operating in a flow mode at reduced pressure (e.g., 20 cm Hg). The counter pulses were monitored and counted for predetermined charge-collection periods.

The primary data consisted of the x-ray production in counts per μC. After correcting for geometry and counter efficiency, the thick-target yield (I) was obtained in units of x rays per proton. By differentiating the expression for the thick-target yield with respect to the limits of integration, an expression can be obtained[1] relating the x-ray production cross section to the thick target yield, stopping power [$S(E)$], and the x-ray absorption coefficient (μ/ρ). This expression may be written

$$\sigma_x = -\frac{1}{n}\frac{dI}{dE}S(E) + \frac{1}{n}\frac{\mu}{\rho}I,$$

where n is the number of atoms per mg. By dividing this cross section by the fluorescence yield, the ionization cross section is obtained. The calculation and the results are shown in Table I. I_α^0 corresponds to L-shell radiation transmitted by a 1.04-mg/cm² copper absorber. Within the restrictions of interpretation based upon the finite widths of both x-ray line and absorption edge, it is taken as a working assumption that only the L_α component is transmitted. (The L_{III} absorption edge lies some 2 eV above the energy of the L_α x-ray component.)

INTERPRETATION

The comparison of data with the currently available L_{III}-shell Born approximation in Fig. 1 results in conclusions consistent with the general trend expected for this calculation.[2,3,5,6] The theory is clearly too high below 0.5 MeV. A somewhat surprising point is the large error which persists above 0.5 MeV, where the Born theory would be expected to be valid as seen qualitatively in the cases of carbon and aluminum in the K shell and neodymium through holmium in the higher energy L shells.[3] An alternative proton description might be the Bang and Hansteen semiclassical deflected-trajectory approach. However, breakdown of the plane-wave description may not account for this high-energy failure. The weakness may come from the description of the bound and ejected electrons which are formed in hydrogenic terms.

[5] R. C. Jopson, Hans Mark, and C. D. Swift, Phys. Rev. **127**, 1612 (1962).

[6] A computer program was developed based upon the works of M. C. Walske, Jr. (thesis, Cornell University) and G. S. Khandewal and E. Merzbacher, Bull. Am. Phys. Soc. **10**, 262 (1965).