L-Shell Ionization by Protons of 1.5- to 4.25-Mev Energy*

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Characteristic L-shell x-rays produced when protons of 1.5- to 4.25-Mev energy are stopped in Ta, Au, Pb, and U have been studied with a NaI scintillator. The absolute cross sections for x-ray production are presented. By correcting these values for Auger transitions, the L-shell ionization cross sections have been determined. At 3 Mev, the x-ray production cross sections are 104, 74, 54, and 24 barns for Ta, Au, Pb, and U, respectively.

I. INTRODUCTION

SINCE protons, deuterons, and alpha particles stopping in matter lose their energy by ionization and excitation processes, characteristic x-rays of the absorber are emitted. Measurement of the cross section for x-ray production, and application of corrections for the Auger effect, allow the cross section for ionization to be obtained. In addition to the characteristic x-rays a small intensity of bremsstrahlung is also produced and has been detected.[1]

The most recent investigation of x-rays produced by heavy particles was made by Lewis, Simmons, and Merzbacher.[2] References to previous work are given in that article. K-shell x-rays produced by protons of Van de Graaff energies on Mo, Ag, Ta, Au, and Pb were studied. The measurements were made with a NaI scintillator. K-shell x-ray cross sections were obtained as a function of proton energy and atomic number. These were converted to K-shell ionization cross sections and compared with the nonrelativistic theoretical ionization cross sections calculated by Henneberg[3] in 1933. There was qualitative agreement between the experimental and theoretical values; however, significant quantitative discrepancies were noted.

Using similar techniques, but with certain experimental modifications dictated by the fact that L x-rays are softer than K x-rays we have measured the cross sections for L-shell ionization by protons up to 4.25 Mev in Ta, Au, Pb, and U. Thin windows were essential for the target chamber and NaI scintillator, and the use of a scintillator about 2 mm thick removed the background due to higher energy gamma and x-rays, but was still 100 percent efficient for the L x-rays. Furthermore, the use of the Dumont 6292 phototube, with its excellent resolution and low noise level permitted good measurements on x-rays to well below 10 kev of energy.

II. EXPERIMENTAL ARRANGEMENT

Figure 1 shows the arrangement of target and detector, and a detailed view of the NaI crystal holder. The target was placed at an angle of 45° with the proton beam from the Van de Graaff accelerator.

Pulses produced in the phototube by single x-ray photons were amplified and fed into a single-channel pulse-height analyzer. Typical curves of counting rate against pulse height, normalized to 10 μcoul, are shown in Fig. 2. The width of the peaks is due partly to the presence of the several lines of the L series which are not resolved, and partly to the finite resolution of the phototube. Tube noise, which begins to rise at about 5 volts on the scale shown, overlaps slightly the low-energy tail of the Ta curve.

The x-rays interact with the scintillator primarily by the photoelectric effect, thereby giving pulses corresponding to the full photon energy, provided the x-rays from iodine in the crystal are also absorbed. To calculate the number I of iodine x-rays which escape if I_0 photons are incident on the crystal, we proceed as follows. Since the beam of incident x-rays is collimated such that it strikes a small area in the center of the crystal face, and since they penetrate only a small percentage of the depth of the crystal, the NaI crystal can be con-

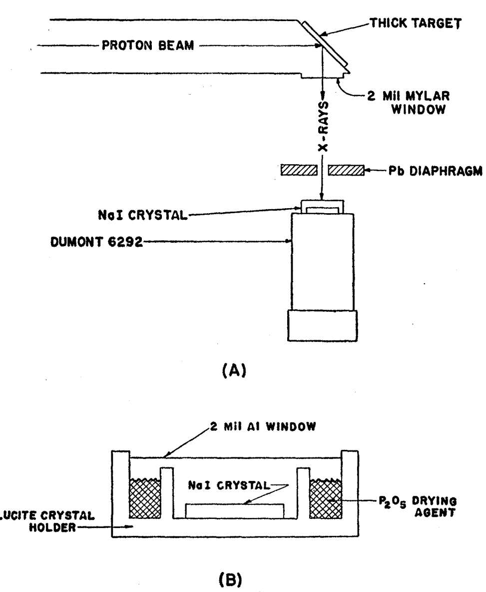

FIG. 1. (A) Arrangement of target and detector. (B) Crystal holder.

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[1] Č. Zupančič and T. Huus (private communication).
[2] Lewis, Simmons, and Merzbacher, Phys. Rev. 91, 943 (1953).
[3] W. Henneberg, Z. Physik 86, 592 (1933).

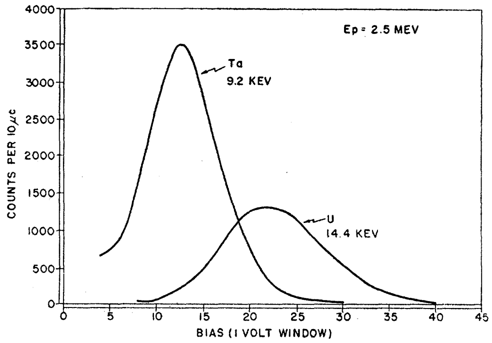

FIG. 2. Typical differential pulse-height spectra of the L-shell x-rays from Ta and U.

sidered a semi-infinite medium. Then,

$$I=\sum_j \alpha_j\beta_j \int_{x=0}^{\infty}\int I_0\mu_1 e^{-\mu_1 x}e^{-\mu_j x/\cos\theta}\frac{d\Omega}{4\pi}dx,$$

where the angle integration is over a solid angle of 2π and the summation is over all the electron shells in the iodine atom ($j=K,L,M,N,O$). α_j is the fraction of incident x-rays absorbed in the jth shell. β_j is the ratio of j-shell x-ray emission to j-shell ionization (the other atoms undergo Auger transitions). x is the distance an incident photon penetrates the crystal before it is absorbed; θ is the angle between the direction of the incident photon and the escaping iodine x-ray. μ_1 is the absorption coefficient of NaI for the incident x-rays; μ_j is the absorption coefficient of the NaI for the x-rays from the jth shell of iodine. Evaluation of the integral gives

$$I=\sum_j \tfrac{1}{2}\alpha_j\beta_j I_0[1-(\mu_j/\mu_1)\ln(1+\mu_1/\mu_j)].$$

Since the x-rays measured in this experiment are of lower energy than the iodine K absorption edge, $\alpha_K=0$. Also, for these energies almost all the incident photons

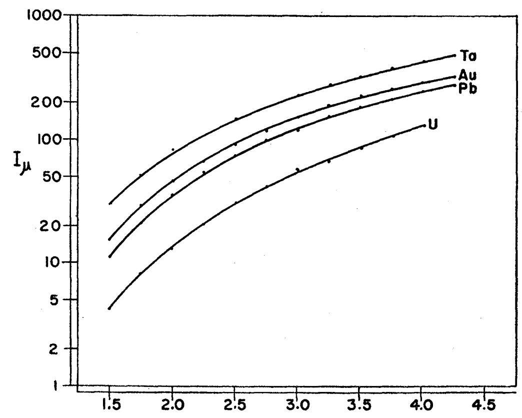

FIG. 3. Total thick target yield I_μ of x-rays per proton of initial energy E_p. I_μ is 4π times the differential yield at 90° to the proton beam, and is uncorrected for self-absorption in the target.

interact with the iodine L shell. Then, to calculate the escape intensity we assume $\alpha_L=1$ and $\alpha_M=\alpha_N=\alpha_O=0$. This assumption leads to an escape intensity slightly greater than the actual case. Now $\beta_L=0.12$, so we have

$$I=0.06I_0[1-(\mu_L/\mu_1)\ln(1+\mu_1/\mu_L)].$$

For Ta, which has the maximum escape of iodine x-rays of the elements investigated, $I=0.015I_0$. Also, due to the finite resolution of the detection apparatus, many of the degraded pulses caused by iodine x-ray escape are counted. Thus, even with the assumption made above, any effect due to escape can be neglected.

III. EXPERIMENTAL RESULTS

An angular distribution of the L x-rays from a thin Au target was taken, and found to be isotropic to at least two percent. Therefore, to obtain I_μ, the total yield of x-rays when one proton of initial energy E_p is

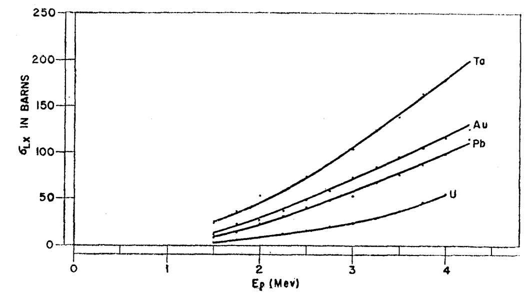

FIG. 4. X-ray production cross sections *vs* proton energy E_p.

stopped in the thick target, the following calculations must be made:

(a) Find the integrated number of counts under the counting rate *vs* bias curve, and divide by the number of current integrator counts (1.03 μcoul per integrator count). This gives the number J of photons counted per 6.42×10^{12} incident protons, listed in column 5 of Table I.

(b) Apply the solid angle correction, which was 5.5×10^5.

(c) Correct for the absorption of the x-radiation in the thin windows and air.

The absorption corrections for the thin windows were determined experimentally by inserting additional window material, two mils of Mylar foil and two mils of aluminum foil between the target and the scintillator. The air absorption correction was calculated, using weighted-average x-ray wavelengths and known absorption coefficients. The over-all absorption correction factors are given in column 6 of Table I. The calculated values of I_μ are given in column 7 of Table I.

To calculate the cross section for x-ray production, one must take account of the self-absorption of the target for its own radiation, and the slowing down of the proton as it penetrates the thick target. Proceeding in the same manner as in reference 2, we obtain the following relation:

$$\sigma[E(x)] = \frac{1}{n}\frac{dI_\mu(x)}{dE}\frac{dE}{d(\rho x)} + \frac{\mu}{n\rho}I_\mu(x).$$

This gives the cross section for x-ray production as a function of known parameters and I_μ, the total yield

TABLE I. Yields of L-shell x-rays.

1 Element	2 Z	3 E_L in kev	4 E_p in Mev	5 J	6 C	7 I_μ
Ta	73	9.2	1.50	0.77×10^3	4.55	3.0×10^{-4}
			1.75	1.3		5.1
			2.00	2.2		8.6
			2.50	3.8		1.5×10^{-3}
			3.00	5.8		2.26
			3.25	7.3		2.8
			3.50	8.2		3.2
			3.75	9.8		3.8
			4.00	11.1		4.3
			4.25	12.3		4.8
Au	79	10.6	1.50	0.71×10^3	2.60	1.6×10^{-4}
			1.75	1.35		3.0
			2.00	2.1		4.7
			2.25	3.2		7.2
			2.50	4.0		8.9
			2.75	5.2		1.17×10^{-3}
			3.00	6.9		1.53
			3.25	8.5		1.9
			3.50	9.6		2.2
			3.75	11.4		2.5
			4.00	13		2.9
			4.25	14		3.1
Pb	82	11.6	1.50	0.64×10^3	2.12	1.16×10^{-4}
			1.75	1.16		2.1
			2.00	1.9		3.5
			2.25	2.9		5.3
			2.50	4.1		7.5
			2.75	5.5		1.0×10^{-3}
			3.00	6.5		1.2
			3.25	8.7		1.6
			3.50	10		1.8
			3.75	11.8		2.1
			4.00	13.5		2.4
			4.25	15.7		2.8
U	92	14.4	1.50	3.2×10^2	1.58	4.5×10^{-5}
			1.75	6.2		8.3
			2.00	9.5		1.3×10^{-4}
			2.25	1.5×10^3		2.0
			2.50	2.3		3.1
			2.75	3.1		4.2
			3.00	3.9		5.3
			3.25	5.0		6.8
			3.50	6.3		8.5
			3.75	7.9		1.07×10^{-3}
			4.00	9.5		1.3

from a thick target. n denotes the number of target atoms per gram, dI_μ/dE is the slope of the curves given in Fig. 3, $dE/d(\rho x)$ is the well-known specific energy loss, and μ/ρ is the mass-absorption coefficient of the target for its own x-rays. The values of these absorption coefficients are rather important, since at high proton energies the second term in the cross-section relation predominates over the first. Again by using weighted averages to obtain the effective wavelength, the absorption coefficients were obtained from relations given by Siegbahn.[4] The values thus obtained were checked experimentally for Ta and Au. The computed average mass-absorption coefficients employed were:

Element	Ta	Au	Pb	U
$(\mu/\rho)_{Av}$ in cm²/g	120	107	98	79.

TABLE II. L x-ray and ionization cross sections.

1 Element	2 E_p in Mev	3 σ_{LX} in barns	4 Auger factor	5 σ_{LI} in barns	6 σ_{KI} in barns
Ta	1.50	24	3.56	84	
	1.75	36		126	
	2.00	54		192	0.017
	2.50	74		265	
	3.00	104		370	0.10
	3.25	124		440	
	3.50	139		495	0.20
	3.75	164		584	
	4.00	177		630	
	4.25	198		705	
Au	1.50	11.6	2.74	32	
	1.75	23		63	
	2.00	27		73	
	2.25	38		103	
	2.50	48		131	0.018
	2.75	59		161	
	3.00	74		203	
	3.25	85		233	
	3.50	96		263	
	3.75	105		288	
	4.00	116		318	
	4.25	126		345	
Pb	1.50	9.1	2.51	23	
	1.75	15		38	
	2.00	24		61	0.0045
	2.25	32		81	
	2.50	42		104	0.013
	2.75	48		122	
	3.00	54		134	0.032
	3.25	68		171	
	3.50	76		191	
	3.75	87		218	
	4.00	99		248	
	4.25	115		288	
U	1.50	3.4	2.22	7.6	
	1.75	6.2		14	
	2.00	9.0		20	
	2.25	13		28	
	2.50	16.5		37	
	2.75	20		45	
	3.00	24		54	
	3.25	30		67	
	3.50	38.0		83	
	3.75	46		103	
	4.00	56		123	

In column 3 of Table II are listed the cross sections for L x-ray production, σ_{LX}. These are plotted as a function of proton energy in Fig. 4. For Au the thick-target results were supplemented by and found consistent with thin-target measurements. An analysis of the errors in the determination of the absolute values

[4] M. Siegbahn, *Spektroskopie Die Roentgenstrallen* (Verlag Julius Springer, Berlin, 1931).

of the x-ray production cross sections indicate they are correct to 20 percent or better for all four elements. The total L-shell ionization cross sections σ_{LI}, listed in column 5 of Table II, are obtained by correcting σ_{LX} for Auger transitions. The Auger factors are not too well known; those used were the ones obtained by Lay in 1934 and given by Burhop.[5]

Table II includes for comparison some K-shell ionization cross sections σ_{KI}, taken from reference 2. These are smaller than the L-shell cross sections by several orders of magnitude. The L-shell cross sections do not fit simple power laws in either proton-energy or atomic-number dependence; however, the variation is slower in both respects than the approximately E^4/Z^{12} dependence of the K shell.

We wish to thank Dr. E. Merzbacher for many helpful discussions of the theory and for his continuing interest in this work.

[5] E. H. S. Burhop, *The Auger Effect* (Cambridge University Press, Cambridge, 1952), p. 55.

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Decay Scheme and Gamma-Gamma Correlations in B^{10}†

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Gamma rays from the deuteron bombardment of beryllium were studied with two scintillation spectrometers operated in coincidence. Gamma rays of energies 2.86, 2.15, 1.43, 1.02, 0.72, and 0.41 Mev, which have previously been associated with the B^{10} nucleus, were identified in single-channel spectra. Coincidences were observed between the following pairs of gamma rays: 2.86−0.72, 2.15−1.43, 1.43−1.43, 1.43−1.02, 1.43−0.72, 1.43−0.41, 1.02−0.72, 1.02−0.41, and 0.72−0.41. The decay scheme obtained from these measurements agrees with the one proposed by Ajzenberg, except for the presence of an additional 1.43-Mev transition between the 3.58- and 2.15-Mev states of B^{10}. A survey was made of the directional angular correlations between several of these coincident radiations.

I. INTRODUCTION

THE gamma rays emitted in the $Be^9(d,n)B^{10*}(\gamma)B^{10}$ reaction have been investigated by Rasmussen *et al.*[1] with a spectrometer of high resolution. From measurements on the energies of the neutron groups, Ajzenberg[2] has determined the excitation energies of the states in B^{10} and has deduced a decay scheme which would account for all the observed gamma rays. The excitation energies have also been obtained by Pruitt *et al.*[3] and Dyer and Bird[4] from observations of the neutron groups in the same reaction, and by Bockelman *et al.*[5] from the inelastic scattering of protons and deuterons by B^{10} nuclei.

In order to establish the decay scheme directly and to investigate some of the gamma-gamma angular correlations, we have searched for coincidences between all possible pairs of gamma rays emitted by the B^{10} nucleus in the Be^9+d reaction at bombarding energies below 0.7 Mev.

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[1] Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949); V. K. Rasmussen, Ph.D. thesis, California Institute of Technology, 1950 (unpublished).
[2] F. Ajzenberg, Phys. Rev. **82**, 43 (1951); Phys. Rev. **88**, 298 (1952).
[3] Pruitt, Swartz, and Hanna, Phys. Rev. **92**, 1456 (1953).
[4] A. J. Dyer and J. R. Bird, Australian J. Phys. **6**, 45 (1953).
[5] Bockelman, Browne, Sperduto, and Buechner, Phys. Rev. **90**, 340 (1953); **92**, 665 (1953).

II. APPARATUS

A thick target of beryllium was bombarded with deuterons from an electrostatic accelerator. The target was located at the center of a cylindrical target chamber, 3 inches in diameter. The brass wall of the chamber was $\frac{1}{32}$ inch thick.

The spectrum of the gamma radiation was studied with a scintillation spectrometer consisting of a cylindrical, sodium iodide crystal, 2 inches long, 1.5 inches in diameter, packed in magnesium oxide powder,[6] and mounted on an RCA 5819 photomultiplier tube. The pulses from the phototube passed through a cathode follower, a linear amplifier, and then were analyzed in a single channel differential analyzer.

For the coincidence work a second scintillation spectrometer was used in coincidence with the first. The second system was similar in every way to the first, except that the crystal was 1.25 inches long. The pulses from the two analyzers operated blocking oscillators which presented uniform pulses to a 6AS6 tube for coincidence analysis. Accidental coincidences were monitored with a separate coincidence circuit, which received delayed pulses from one analyzer and undelayed pulses from the other.

[6] C. J. Borkowski and R. L. Clark, Rev. Sci. Instr. **24**, 1046 (1953).