PHYSICAL REVIEW VOLUME 134, NUMBER 4A 18 MAY 1964

Soft X-Ray Production by 1.5-MeV Protons

W. T. Ogier, G. J. Lucas,* J. S. Murray,* and T. E. Holzer*
Pomona College, Claremont, California
(Received 31 December 1963)

Thick-target yields of x rays with wavelengths from 1.5 to 44 Å have been measured as functions of bombarding proton energy near 1.5 MeV. X-ray production cross sections computed from these yields are in satisfactory agreement with existing theoretical excitation cross-section calculations insofar as current estimates of fluorescence yields permit comparisons to be made. Yields at 1.5 MeV of the ultrasoft x rays measured were, in quanta per proton steradian: Al_K, 3.5×10^{-3}; Cu_L, 9×10^{-4}; C_K, 4.5×10^{-3}.

INTRODUCTION

Interest in determination of x-ray yields from proton-bombarded targets revived with the advent of scintillation counting. Extensive early investigations by Lewis, Simmons, and Merzbacher[1] and by Bernstein and Lewis[2] were followed by a number of experimental and theoretical studies. The state of the field was then reviewed and analyzed in a satisfying way for proton energies above one MeV by Merzbacher and Lewis.[3] Subsequent interest has centered on energies below one MeV for which the Born approximation does not yield completely satisfactory results.[4,5] The use of scintillation counters in these modern measurements served to limit observations to x rays with quantum energies of 4.5 keV or more.

The availability of thin-window proportional counter techniques makes possible quantitative study of yields of x rays with quantum energies at least as low as 280 eV.[6] Reports of such proton-yield measurements have only recently begun to appear.[7] In this investigation yields of a number of K and L x-ray bands with quantum energies between 8000 and 280 eV (1.5 to 44.6 Å) were measured for bombarding proton energies between 1.2 and 1.6 MeV. These yield functions are used to calculate cross sections for x-ray production at 1.5 MeV. The ratio of production cross section to excitation cross section is the fluorescence yield. Current estimates of excitation cross section and fluorescence yield both involve uncertainties in the soft x-ray region. These results do not resolve either uncertainty, therefore, but they fit well with reasonable estimates of both parameters.

* National Science Foundation undergraduate research participant.

[1] H. W. Lewis, B. E. Simmons, and E. Merzbacher, Phys. Rev. **91**, 943 (1953).

[2] E. M. Bernstein and H. W. Lewis, Phys. Rev. **95**, 83 (1954).

[3] E. Merzbacher and H. W. Lewis, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 166.

[4] S. Messelt, Nucl. Phys. **5**, 435 (1958).

[5] R. C. Jopson, H. Mark, C. D. Swift, and M. A. Williamson, Phys. Rev. **131**, 1165 (1963); **127**, 1612 (1962) contains a recent bibliography.

[6] R. M. Dolby, Brit. J. Appl. Phys. **11**, 64 (1960).

[7] J. M. Khan and D. L. Potter, Phys. Rev. **133**, A890 (1964).

EXPERIMENTAL PROCEDURE

Targets of the metals investigated were bombarded inside the main tank of the 23-in. cyclotron. This cyclotron, a prototype model, employs radial sector Thomas focusing without the usual tapering of the gap at larger radii to maintain orbit synchronism. Since the sector focusing is strong in the vertical direction for eccentric orbits as well as for symmetric orbits, a target inside the tank is exposed to a considerable spectrum of energies which can be limited somewhat by careful collimating of the incident beam at the target position. Such collimation was provided, and since negligible currents are found in the symmetric orbits at large radii, the angle of collimation was set at approximately 83° with the radial direction in order to select the more energetic eccentric orbits. The proton energy was varied by moving the target assembly radially. In the absence of computed energies, the yield of tantalum L x rays was used to calibrate the beam energy using the data of Bernstein and Lewis[2] extrapolated below 1.5 MeV with the aid of the calculations of Merzbacher and Lewis.[3] The surface of the target was set optically in each case at the angle of specular reflection between the beam direction and the radial direction along which x rays were viewed. The proton and the resulting x ray thus traveled equal distances in the target material.

The x rays were counted outside the magnetic field at the end of a 129-cm evacuated drift path by means of a flow proportional counter of standard design using P-10 gas (10% methane, 90% argon).[8] The window aperture was a single 0.063-in.-diam hole inside the vacuum, which thus subtended a solid angle at the target of 1.21×10^{-6} sr. The window material, 0.00025-in. aluminized Mylar, was bonded with epoxy cement over a slightly larger aperture set just behind the window. One corner of the Mylar was folded under to ground the aluminized surface. This structure gave good counting rates with proton currents smaller than one microampere in all cases except that of tantalum L radiation. Because of the importance of the tantalum data for calibration, it was checked using an aluminum window of larger aperture. The two runs were in very close agreement.

[8] C. F. Hendee, S. Fine, and W. B. Brown, Rev. Sci. Instr. **27**, 531 (1956).

Yields were determined by counting the pulses corresponding to the x-ray band desired with a single-channel pulse-height analyzer while proton current was being monitored with a calibrated galvanometer. The pulses corresponding to a particular band were well resolved, but the structure within bands was not visible. The *bremsstrahlung* background was apparently very small and was ignored. In particular, in the case of carbon-K radiation a clear minimum existed in the pulse-height spectrum between the counting pulses and the amplifier noise. The discrimination level was set just above the noise. The yields reported from the x rays with quantum energy greater than the ionization potential of argon include the attenuated argon-K escape pulses.

Counter efficiencies due to window and gas absorption were computed from the measured geometry of the counter using the mass absorption-coefficient interpolations of the data of Allen by Henke, White, and Lundberg.[9] The path length in the argon was 2.26 cm. The computed efficiencies are recorded in the first column of Table I. The transmission factor of the Mylar for carbon-K radiation was thus estimated to be 0.04. This transmission was checked experimentally by placing a second layer of the same material in the x-ray path in the vacuum. The measured transmission varied from place to place in the film. The value adopted was 0.038 ± 0.01.

EXPERIMENTAL RESULTS

The yields of x rays, Y_μ, in quanta per proton steradian at 1.5-MeV bombarding energy are given in the second column of Table I and the yields as functions of bombarding energy are presented graphically in Fig. 1. Considerable uncertainty lies in the determination of proton energy, since the collimated proton beam had a spread in energy of some 0.2 MeV and the energy calibration below 1.5 MeV is based on extrapolation. The curves for tantalum-L and iron-K radiation both fit well the results of Merzbacher and Lewis,[3] but there is a sizable discrepancy in the data for titanium K. In the preliminary phases of this work the yields from various titanium targets were compared with those from tantalum and iron, always with essentially the results reported.

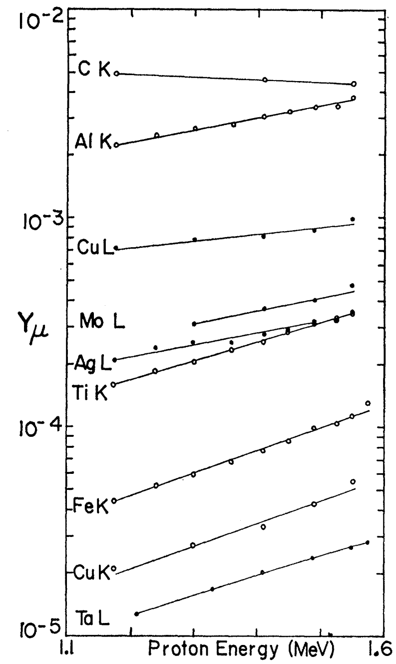

FIG. 1. Thick-target characteristic x-ray yields, Y_μ, in quanta per proton sr as functions of proton bombarding energy. Proton and quantum traveled equal distances in the target material.

TABLE I. Data at 1.5 MeV.

	Counter efficiency	Y_μ quanta / proton·sr	μ/ρ	σ_x (1.5 MeV) cm²	Yield factor
C_K	0.038	4.5×10^{-3}	3000	3×10^{-21}	0.007
Al_K	0.45	3.5×10^{-3}	330	1.0×10^{-21}	0.065
Ti_K	0.84	3.2×10^{-4}	114	1.1×10^{-22}	0.24
Fe_K	0.54	1.0×10^{-4}	71.2	3.8×10^{-23}	0.35
Cu_K	0.31	4.5×10^{-5}	50.9	2×10^{-23}	0.4
Cu_L	0.057	9×10^{-4}	1000	1.3×10^{-21}	0.01
Mo_L	0.55	4×10^{-4}	630	6×10^{-22}	0.06
Ag_L	0.40	3.2×10^{-4}	460	4.0×10^{-22}	0.10
Ta_L	0.31	2.5×10^{-5}	150	2.7×10^{-23}	0.30

The cross section for x-ray production $\sigma_x(E)$ is computed from the yield curve by the familiar formula[3]

$$\sigma_x(E)=\frac{4\pi}{n}\left(\mu Y_\mu+\frac{dY_\mu}{dE}\frac{dE}{dx}\right), \qquad (1)$$

where n is the number of atoms per unit volume and μ the linear absorption coefficient. The stopping powers, dE/dx, are readily available,[10] but the self-absorption coefficients μ are not nearly so easy to obtain, particularly for the L x rays. The K self-absorption coefficients used are based on the Henke, White, and Lundberg interpolation formula[9] and the L coefficients on the Norelco extrapolation of the data of Allen and others.[11] Even the data itself is open to question.[12] The estimated values of μ/ρ used are recorded in the third column of the table, and the resulting calculated x-ray production cross sections in the fourth column.

DISCUSSION

Theoretical excitation cross sections were derived by Bethe and Walske[13] on the basis of screened hydrogenic

[9] B. L. Henke, R. White, and B. Lundberg, J. Appl. Phys. **28**, 98 (1957).

[10] W. Whaling, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.

[11] S. J. M. Allen *et al.*, Norelco Reporter, May-June 1962 (unpublished).

[12] B. A. Cooke, K. A. Pounds, P. C. Russell, and E. A. Stewardson, Proc. Phys. Soc. (London) **79**, 883 (1962).

[13] M. C. Walske, Phys. Rev. **101**, 940 (1956).

wave functions. The resulting integrals depend critically on the minimum energy which must be transferred to the atomic state in question in order to produce excitation. The effect of screening on this energy is expressed by θ, the ratio of the ionization potential of the state in question to the theoretical ionization potential in the absence of outer screening. Merzbacher and Lewis[3] have computed and plotted excitation cross section as a function of proton energy for various values of θ. Comparing their computed curves with experimental data, they found that the predicted cross sections were too large and that the data was consistent with empirical values of θ_K and θ_L of 0.85 and 0.7, respectively, both essentially independent of atomic number. Both values correspond to effective minimum energy transfers higher than the ionization potentials, particularly for the light elements. The extrapolation of this result from the 1.5-Å wavelengths at which it was found to longer wavelengths is a doubtful procedure. Some support may be found in observations of effective thresholds for electron excitation. For example, Dolby[6] observes effective bombarding energy thresholds for strong K x-ray production of about 2200 and 400 eV from aluminum and carbon, respectively. Both correspond roughly to unit values of θ_K. The ionization potential does not appear to be a valid effective minimum for rapid energy transfer.

The ratios of observed x-ray production cross sections to theoretical excitation cross sections obtained from the curves for $\theta_K=0.85$ and $\theta_L=0.7$ plotted by Merzbacher and Lewis[3] are tabulated as yield factors in the last column of the table. To the extent that confidence can be placed in the empirical values of θ these factors are fluorescence yields. Current estimates of soft K-fluorescence yields are classifiable into a low set of values based on extrapolation of measurements with heavier metal targets[14,15] and a considerably higher set of values based on data from argon[16] and a number of theoretical calculations including recently a screened hydrogenic wave function calculation by Callan.[17] The K yield factors in the table from copper through aluminum fit well slightly below Callan's curve. Very little data on L fluorescence yields is available.[18] Since the trajectory of a massive particle in a target is inherently easier to handle theoretically than that of an electron, measurements such as these are a potentially useful way of determining fluorescence yields. They would be worth repeating with more precise apparatus.

The yield of aluminum-K x rays at 1.5 MeV corresponds to a production efficiency of 1.4×10^{10} quanta per joule sr, about the maximum efficiency obtainable. On the other hand, 1.5 MeV is about six times the proton energy required for maximum production efficiency from carbon. The maximum efficiency from carbon is readily estimated with the aid of the measured yield and the excitation cross section curve to be approximately 10^{11} quanta per joule sr. The carbon efficiency is comparable to the efficiency attainable with electron bombardment,[19] but the aluminum efficiency is smaller by a factor of four or more. The proton efficiencies can be raised somewhat by irradiating with protons at grazing incidence. Since the resulting radiation is nearly free of *bremsstrahlung*, it appears that proton excited sources might be superior to filtered electron excited sources in a few applications.

ACKNOWLEDGMENTS

We are indebted to James Backman, Elliott Bloom, and William Soldwisch for valuable contributions to various phases of this work as National Science Foundation undergraduate research participants. We also acknowledge the contribution of Professor Burton L. Henke, without whose advice and encouragement this project would not have been possible.

[14] E. H. S. Burhop, J. Phys. Radium **16**, 625 (1955).
[15] H. L. Hagedoorn and A. H. Wapstra, Nucl. Phys. **15**, 146 (1960).
[16] T. Watanabe, H. W. Schnopper, and F. N. Cirillo, Phys. Rev. **127**, 2055 (1962).
[17] E. J. Callan, Phys. Rev. **124**, 793 (1961).
[18] A. A. Konstantinov, T. E. Sazonova, and V. V. Perepelkin, Bull. Acad. Sci. USSR, Phys. Ser. **24**, 1472 (1960).
[19] A. J. Campbell, Proc. Roy. Soc. (London) **A274**, 319 (1963).