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Excitation of Characteristic *K* X-Rays from Elements by Protons, Deuterons, and Alpha Particles*

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The excitation of characteristic *K* x-rays from Cu and Ag by bombardment of protons, deuterons, and alpha particles has been studied. The charged particles are accelerated by an electrostatic generator and the resulting characteristic *K* x-rays from thin targets are detected by a proportional counter of good resolution and known efficiency. The counter used can count x-rays of energy between 2.0 kev and 50.0 kev with high efficiency. The pulses from the counter are analyzed by a fifty-channel kick-sorter and the number of x-ray quanta produced is determined by well-defined differential curves. After correcting for the Auger transition, the absolute cross section for *K*-shell ionization is measured for the accelerated particles of different energies and compared with the theoretical cross section obtained by using the formula of Lewis, Simmons, and Merzbacher deduced from the theory of Henneberg.

I. INTRODUCTION

When protons, deuterons, and alpha particles pass through matter, they lose energy by ionization and excitation of the atoms. Furthermore, they may eject electrons from the inner shells of the atoms of the elements through which they pass and, in such cases, it is expected that characteristic x-rays will be emitted.

The first experimental detection of such characteristic x-rays was made by Chadwick.[1] He detected a small amount of characteristic x-rays when elements were bombarded by alpha particles from radium *C*. No quantitative conclusions could be arrived at because of intense gamma radiation. The most recent investigation of such x-rays has been made by Lewis, Simmons, and Merzbacher,[2] in which references to previous works are also given. They determined the absolute cross section for *K*-shell ionization from thick targets of five heavy elements, Mo, Ag, Ta, Au, and Pb, by protons of energies between 1.7 Mev and 3.0 Mev. The protons are accelerated by a Van de Graaff machine and the x-rays produced are detected by a photomultiplier tube with a NaI crystal. The absolute cross sections for *K*-shell ionization are measured for the different proton energies and they are compared with the theoretical cross sections obtained from the theory of Henneberg.[3] Their results are in general agreement with the theory except that the absolute values of the cross sections are larger than the theory predicts, by a factor of four or five, for elements of higher *Z*. This might be due to the fact that the x-rays are detected by a photomultiplier tube with a NaI crystal and the inherent difficulty of making absolute deductions from thick-target yields. The photomultiplier tube has a high efficiency for gamma rays and other background radiations.

The present work consists of the measurement of the absolute cross section for the production of *K* x-rays from thin targets of Cu and Ag by protons, deuterons, and alpha particles of energies between 0.4 Mev and 1.0 Mev. The experimental cross sections for the *K*-shell ionization of Cu and Ag are compared with the theoretical cross section obtained from the theory of Henneberg. The bombarding particles are accelerated by an electrostatic generator (Van de Graaff). The resulting x-rays are detected by a proportional counter which has good resolution and high efficiency for x-rays of energy from 2.0 kev to 50.0 kev and has low efficiency for gamma rays. Thus the background is negligible in counting x-rays with this counter.

The absolute cross section for *L*-shell ionization from a thin target of Ag, has been measured also and will be

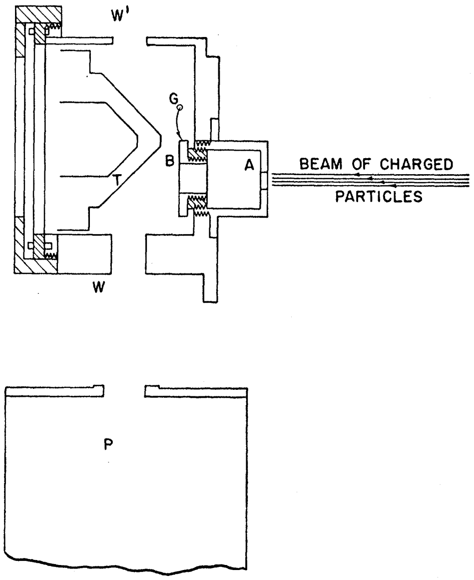

FIG. 1. Experimental arrangement. *P*—counter; *W*—window for examining radiations; *W*¹—duplicate window; *T*—target holder; *B*—secondary electron suppressor; *G*—glass to metal seal; *A*—entrance for charged particles.

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* This work forms a part of the thesis submitted by the author for the degree of Doctor of Philosophy at the University of London.

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[1] J. Chadwick, Phil. Mag. **25**, 193 (1913).

[2] Lewis, Simmons, and Merzbacher, Phys. Rev. **91**, 943 (1953).

[3] W. Henneberg, Z. Physik **86**, 592 (1933).

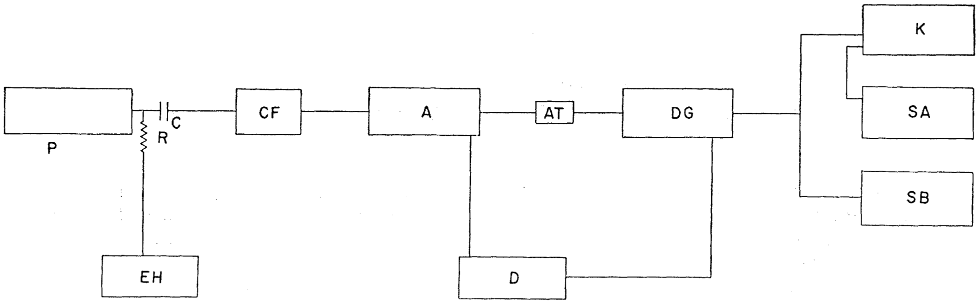

Fig. 2. Block diagram for counting circuits. *P*—counter; *EH*—stabilized high tension; *CF*—preamplifier and cathode follower; *A*—linear amplifier; *D*—discriminator; *AT*—attenuator; *DG*—delay and gate; *K*—pulse analyzer; *SA* and *SB*—scalers.

published at some later date. While this work was in progress, Bernstein and Lewis[4] have studied the excitation of *L*-shell ionization in thick targets of four heavy elements, Ta, Au, Pb, and U, by protons of energies between 1.5 Mev and 4.25 Mev.

Very recently Hansteen and Messelt[5] have measured *K* x-rays from thick targets of Cu and Mo produced by protons of energies between 0.2 Mev and 1.6 Mev. Their results for Cu agree with ours at 0.5 Mev, but at 1 Mev the results are higher by a factor of two.

II. EXPERIMENTAL ARRANGEMENT

Figure 1 shows the general arrangement of the target and the proportional counter. (The target chamber and counter are not drawn to the same scale.) The target chamber is connected to the electrostatic generator with a standard flange. The focussed beam of accelerated particles enters the target chamber through a small entrance hole $\frac{9}{32}$ in. in diameter. To ensure the correct reading of the beam current, a device is introduced for the suppression of secondary electrons. This is achieved by providing between the entrance hole and the target holder an insulated circular copper ring of diameter about twice that of the entrance hole. Provision is made to apply a negative potential to the ring through a glass-to-metal seal. The target chamber is so designed that the proportional counter can be mounted in a symmetrical position along the axis of the chamber window at 90° to the axis of the beam. The window of the chamber is made of cellophane, of thickness 3 mg/cm^2. The x-rays are detected by a counter 12 in. long and of $3\frac{7}{8}$-in. internal diameter and the resulting pulses are counted and recorded. To ensure that only the x-rays originating from the target entered the window of the counter, the counter was covered with five layers of lead, each 3 mm thick, leaving only the window exposed.

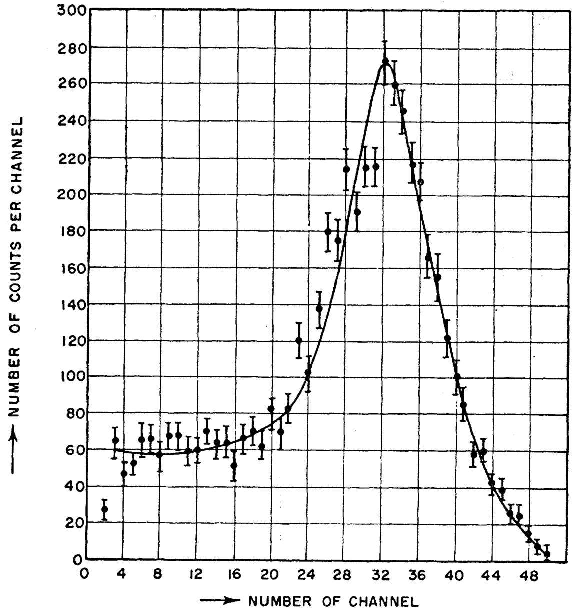

Fig. 3. Spectrum of Cu *K* x-rays by protons of 0.4 Mev. Kick-sorter bias—12 volts.

Figure 2 shows the block diagram for the counting circuits. The pulse from the counter is amplified by a linear amplifier through a cathode follower. One of the two outputs goes to an external discriminator unit and the other goes to a delay and gate unit through an attenuator. The pulses from the discriminator trigger the gate. The resulting pulse from the gate is divided into two parts. One is fed into a fifty-channel kick-sorter and the other goes to a scaler. There is also an arrangement to count all the pulses registered in the kick-sorter with another scaler. The main purpose of using the extra discriminator, gate, etc., is to ensure by introducing a cutoff that the scaler SB records only pulses in exactly the same position of spectrum as the kick-sorter, so that it can be used for normalization. This arrangement has to be used because the kick-sorter is not fast enough to register all the x-ray quanta detected by the counter. Each channel of the kick-sorter is 0.4 volt wide.

III. MEASUREMENT OF THE CROSS SECTION

A thin target less than one mg/cm^2 thick was bombarded by accelerated particles. To determine the cross section for the production of *K* x-rays from the target, the following calculations were made. (The

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

[5] J. M. Hansteen and S. Messelt, *Nuclear Physics* (North Holland Publishing Company, Amsterdam, 1957), Vol. 2, p. 526.

angular distribution is assumed to be isotropic—see Bernstein and Lewis.[4])

1. The total number of x-ray quanta was determined from the area of the peak of the differential curve of the kick-sorter.
2. Corrections for absorption of x-rays in the target, in the window of the chamber, in air, in the window of the counter, and in the insensitive region at the end of the counter were made.
3. Solid-angle evaluation was made.
4. The number of incident particles was determined from the current-integrator reading. The two ranges of the current integrator which were used have sensitivities of 0.70±0.035 and 0.0877±0.004 microcoulomb per count. This was calibrated with a constant current source.
5. The number of target nuclei per cm^2 was determined from the thickness of the target.
6. The efficiency of the proportional counter was measured experimentally and checked by theoretical considerations. For the study of the excitation of characteristic *K* x-rays of Cu, the proportional counter was filled with a mixture of 90% argon and 10% carbon dioxide, to a pressure of 25 cm of Hg. The *K* x-rays of Cu have an energy of 8.1 kev and the efficiency of the counter for such x-rays is 65.0%. However, the *K* x-rays of Ag have an energy of 24.0 kev and so the efficiency of the counter filled with 25 cm of Hg is very low. Besides, quite large numbers of photoelectrons ejected by the *K* x-rays of Ag escape from the counter and so it is necessary to fill the counter to a higher pressure. To study the *K* x-rays of Ag, the counter was filled with a mixture of 90% argon and 10% carbon dioxide to a pressure of 60 cm of Hg. The efficiency at this pressure is only 20%. However, a greater pressure would require a higher voltage with an accompanying increase in noise.

Figures 3, 4, and 5 show the typical spectrum of Cu *K* x-rays obtained with the fifty-channel kick-sorter. Figure 3 also indicates the statistical fluctuations. The characteristic *K* x-rays of Cu are identified by a critical absorption measurement and by the comparison of its spectrum with that of 8.1-kev x-rays from an active Zn^{65} source. Figure 6 is the spectrum of Ag *K* x-rays obtained with the fifty-channel kick-sorter. These were also identified by a critical absorption measurement. Since the cross section for the production of *L* x-rays in Ag by protons is very large, a 0.005-in.-thick iron foil was interposed between the target chamber and the proportional counter to absorb all the *L* x-rays of silver, which would otherwise produce "pile-up" of pulses in the counting circuits. This ensures that the number of x-ray quanta counted from the differential curve is due only to the *K* x-rays of Ag. The absorption of the *K* x-rays of Ag in the iron foil was corrected by the known mass absorption coefficient of iron.

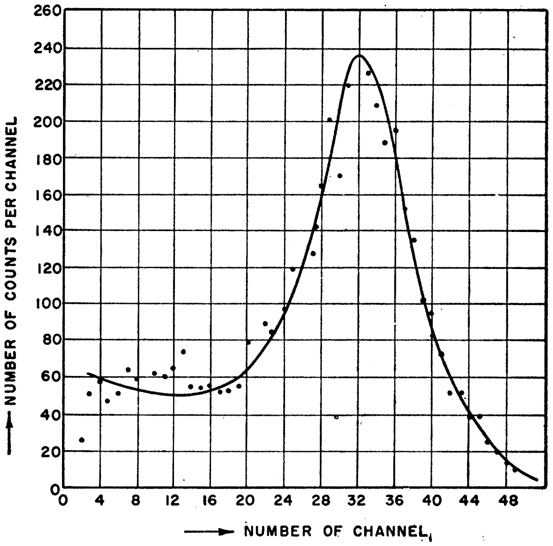

FIG. 4. Spectrum of Cu *K* x-rays by deuterons of 0.6 Mev. Kick-sorter bias—12 volts.

The cross section for the production of *K* x-rays was finally corrected for the Auger transition, and the absolute cross section for the production of *K*-shell ionization so determined was compared with the theoretical cross section, calculated by use of the formula used by Lewis, Simmons, and Merzbacher. The experimental results are given in Table I and the analysis of the errors indicates that the accuracy of the measurement is ±12.0%.

IV. DISCUSSION AND CONCLUSIONS

When an element is bombarded by accelerated protons, deuterons, or alpha particles, the resulting x-radiation might be due to any of the following causes: (1) Characteristic x-rays of the element

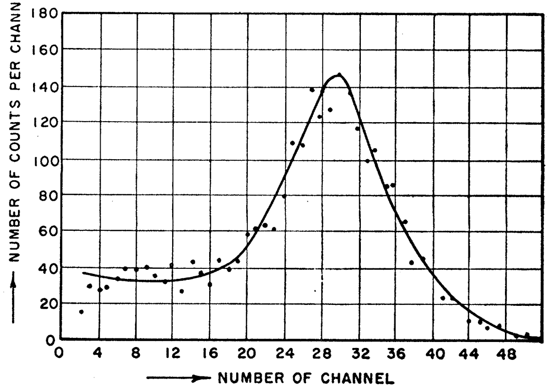

FIG. 5. Spectrum of Cu *K* x-rays by alpha particles of 0.7 Mev. Kick-sorter bias—12 volts.

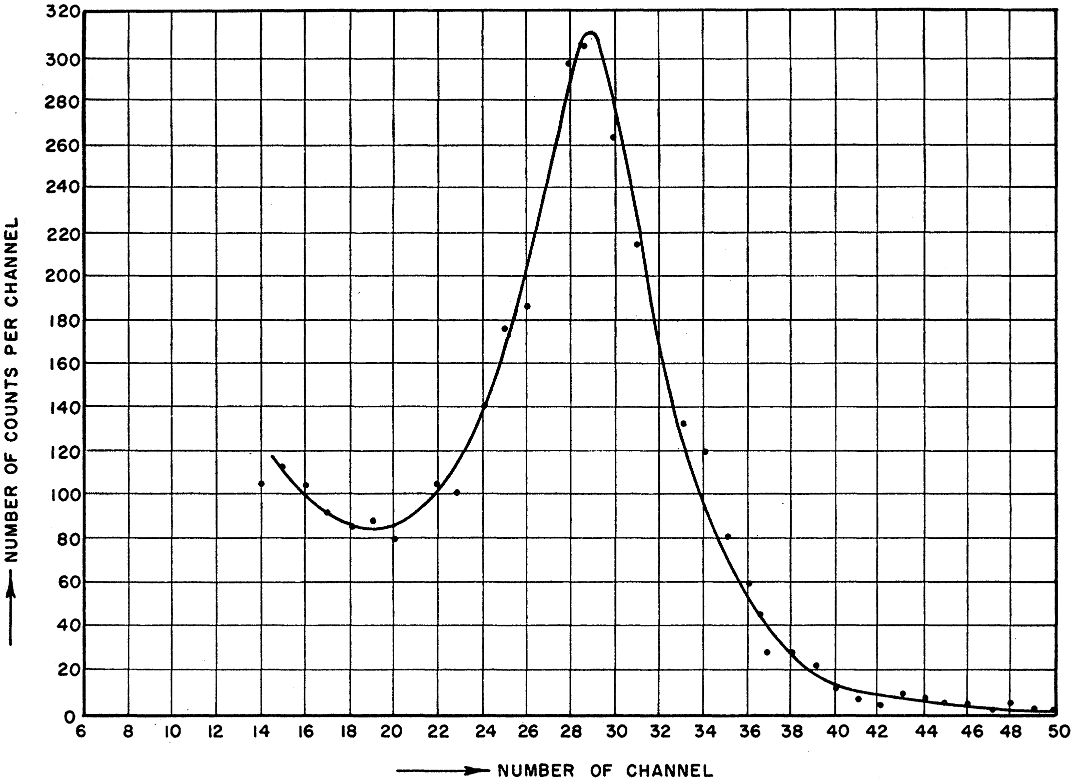

FIG. 6. Spectrum of Ag *K* x-rays by protons of 0.7 Mev. Kick-sorter bias—5 volts.

resulting from the ejection of electrons from the inner shells of the atom by the incoming particles; (2) the x-rays produced by *K* capture following a process involving the formation of the compound nucleus; (3) the x-rays produced by internal conversion of the gamma rays produced by the excited states of the target elements (Coulomb excitation), and (4) bremsstrahlung from the accelerated particle.

While measuring the cross section, it is made clear beyond doubt by the critical-absorption measurement that the x-rays counted belong to the *K* x-rays of the elements bombarded. Thus the cross section measured is that of the *K* x-rays of the target element.

According to Blatt and Weisskopf,[6] the cross sections for compound-nucleus formation in Cu and Ag by protons, deuterons, and alpha particles with energies between 0.4 Mev and 1.0 Mev are very small. So the formation of a compound nucleus and the subsequent emission of *K* x-rays in these elements by the *K*-capture process is negligible.

When Cu and Ag targets are bombarded by accelerated particles, there may be Coulomb excitation and subsequent emission of characteristic x-rays due to internal conversion. The measurements made on Coulomb excitations by a number of workers[7–10] indicate that they are very small.

From the work of Fisher[11] on electron bremsstrahlung from Au, the cross sections for bremsstrahlung due to protons, deuterons, and alpha particles of energies between 0.4 Mev and 1.0 Mev from Cu and Ag can be estimated, and they are of the order of 1×10^{-31} cm^2. Thus it is clear that in our investigations, the cross sections measured are only those for the production of *K* x-rays by ejection of electrons from *K*-shells.

The experimental cross section is found to increase with increasing energy of the incident particles. The increase of the cross section with increasing energy is proportional to the fourth power of energy within the range of the energies investigated. This is in agreement with the theory of Henneberg[3]. While there is general agreement between the experimental and the theoretical cross sections in the case of protons and deuterons, the experimental value is smaller than the theoretical by a factor of three or so. The agreement does not improve even if our measured cross section is corrected for 45°

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[6] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 352.

[7] R. Huby and H. C. Newns, Proc. Phys. Soc. (London) **A64**, 619 (1951).

[8] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **93**, 351 (1954).

[9] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **95**, 861 (1954).

[10] S. W. Barnes and P. W. Aradine, Phys. Rev. **55**, 50 (1939).

[11] P. C. Fisher, Phys. Rev. **92**, 420 (1953).

TABLE I. Absolute cross section in cm^2 for *K*-shell ionization.

Element	Target thickness mg/cm^2	Energy of x-rays kev	Incident particles	Energy of particles Mev	Experimental cross-section σ, cm^2	Theoretical cross-section σ_{th}, cm^2	σ_{th}/σ
$_{29}$Cu	0.125	8.1	Protons	0.4	0.406×10^{-24}	1.7×10^{-24}	4.15
				0.5	0.84×10^{-24}	3.49×10^{-24}	4.22
				0.6	1.75×10^{-24}	6.19×10^{-24}	3.55
				0.7	2.73×10^{-24}	9.2×10^{-24}	3.4
				0.8	4.37×10^{-24}	13.9×10^{-24}	3.17
				0.9	7.7×10^{-24}	18.3×10^{-24}	2.4
				1.0	11.1×10^{-24}	25.5×10^{-24}	2.3
			Deuterons	0.6	2.2×10^{-25}	6.5×10^{-25}	2.93
				0.7	4.36×10^{-25}	10.7×10^{-25}	2.45
				0.8	8.85×10^{-25}	17.0×10^{-25}	1.92
				0.9	12.1×10^{-25}	25.0×10^{-25}	2.06
				1.0	18.07×10^{-25}	34.6×10^{-25}	1.96
			α-particles	0.7	2.27×10^{-26}	38.0×10^{-26}	16.7
				0.8	3.72×10^{-26}	61.2×10^{-26}	16.6
				0.9	7.12×10^{-26}	92.0×10^{-26}	13.1
				1.0	10.38×10^{-26}	132.0×10^{-26}	12.7
$_{47}$Ag	0.5	24.0	Protons	0.6	4.16×10^{-27}	23.0×10^{-27}	5.5
				0.7	10.18×10^{-27}	40.3×10^{-27}	3.95
				0.8	17.6×10^{-27}	64.0×10^{-27}	3.63
				0.9	33.57×10^{-27}	98.0×10^{-27}	2.91
				1.0	46.5×10^{-27}	136.0×10^{-27}	2.94

inclination of the target. In the case of alpha particles, there is a significant difference. The experimental value is smaller than the theoretical by a factor of twelve or so.

This discrepancy between the cross sections for protons and alpha particles cannot be attributed to experimental measurement because the same target and the same counting equipment have been used throughout.

There is also some difference between our results and the results of Lewis, Simmons, and Merzbacher for *K*-shell ionization of Ag by protons. The experimental cross section obtained by them for protons of 1.7-Mev energy is smaller than the theoretical value but it rises rapidly with increasing energy and at 2.28 Mev the experimental value is larger than the theoretical by a factor of about three. In our measurement for Ag using protons with energies between 0.6 Mev and 1.0 Mev, the experimental value is smaller than the theoretical. However, it rises more rapidly than the theoretical cross section with energy and may agree with that of Lewis, Simmons, and Merzbacher in the region of 1.7 Mev.

Henneberg[3] used Born's approximation to calculate the theoretical cross section for the production of characteristic x-rays in elements by positively charged particles. He tested the validity of his theoretical cross section in the case of *K*-shell ionization of Al by polonium alpha particles, by comparing it with the experimental value of Bothe and Franz.[12] He found that the theoretical cross section is larger than the experimental cross section by a factor of about three. Henneberg considered this to be in reasonable agreement with his theory.

Therefore in our experiment there is general agreement between the theory and measurement in the case of protons and deuterons, but there is a significant difference in the case of alpha particles. It appears that the theory of Henneberg, which is valid for singly charged particles, leads to a discrepancy when used for particles of multiple charge. This discrepancy between the theory and experiment suggests that a more exact theoretical treatment at low energies would be desirable.

V. ACKNOWLEDGMENTS

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[12] W. Bothe and H. Franz, Z. Physik 52, 466 (1929).