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Cross Sections for L-Shell Ionization of Ag by Protons, Deuterons, and Alpha Particles*

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A thin target of Ag is bombarded by protons, deuterons, and alpha particles of energies between 0.4 Mev and 1.0 Mev. The charged particles are accelerated by a Van de Graaff machine and the resulting L x-rays of Ag are detected by a proportional counter of good resolution and high efficiency. The pulses from the counter are analyzed by a fifty-channel pulse-height analyzer 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 L-shell ionization is measured. The absolute cross section of L-shell ionization is larger than the K-shell ionization by a factor of 10^4 for the same proton energy. In the absence of a theoretical treatment for L-shell ionization, an empirical formula similar to the K-shell ionization formula is suggested.

I. INTRODUCTION

WHEN an element is bombarded by accelerated positively charged particles, characteristic x-rays of the element are produced. These consist of K x-rays as well as L x-rays of the element bombarded. Bothe and Franz[1] detected L radiations from elements of atomic number higher than 34, in addition to the K-shell radiation, by the use of natural alpha particles. The x-rays were detected by a Geiger counter and identified by the measurement of mass absorption coefficients in Al. In each case the excitation was found to increase with increasing energy of the alpha particles. Absolute measurements could not be made. Gerthsen and Reusse[2] compared the yield of K radiation of Al with L radiations of Se by accelerated protons. Livingston, Genevese, and Konopinski[3] studied qualitatively the production of such x-rays excited by cyclotron-accelerated protons of 1.79 Mev and obtained results similar to those of Bothe and Franz for protons of energy up to 1.76 Mev. They examined L x-rays for elements of atomic number higher than 40.

In 1941, Cork[4] made a similar investigation using 10-Mev deuterons from a cyclotron and detected the radiations by a photographic technique. He studied the excitation of characteristic L x-rays from different elements, but no definite quantitative measurements could be made.

The most recent investigation of L-shell ionization has been made by Bernstein and Lewis[5] using protons accelerated by a Van de Graaff generator. They 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 using a photomultiplier tube as a detector. Absolute cross sections were found to increase with increasing proton energy.

The present work consists of the measurement of the absolute cross sections for the production of L x-rays from a thin target of Ag by protons, deuterons, and alpha particles, of energies between 0.4 Mev and 1.0 Mev. The charged particles are accelerated by a Van de Graaff machine and the resulting L x-rays are detected by a proportional counter of good resolution and high efficiency. The pulses from the counter are analyzed by a fifty-channel pulse-height analyzer 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 L-shell ionization is determined.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement and the counting circuits are exactly the same as those used in the study[6] of the excitation of characteristic K x-rays from elements by protons, deuterons, and alpha particles. Similar precautions were also adopted for shielding and the suppression of secondary electrons.

III. IDENTIFICATION OF L X-RAYS OF Ag

The L x-rays of Ag consist of a very large number of lines. The average wavelength for the L x-rays of Ag is 3.84 A and its average energy is 3.24 kev (see Compton and Allison[7]). The identification of L x-rays of Ag can be made by two methods: (1) by comparison of the pulse height of L x-rays of Ag with the pulse height of K x-rays of Cu, and (2) by measurement of the mass absorption coefficient in aluminum.

1. Comparison of the Pulse Height

K x-rays of Cu have an energy of 8.1 kev and L x-rays of Ag have an energy of 3.24 kev. Thus, if the counting

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[1] W. Bothe and H. Franz, Z. Physik **52**, 466 (1929).
[2] C. Gerthsen and W. Reusse, Physik. Z. **34**, 478 (1933).
[3] Livingston, Genevese, and Konopinski, Phys. Rev. **51**, 835 (1937).
[4] J. M. Cork, Phys. Rev. **59**, 957 (1941).
[5] E. M. Bernstein and H. W. Lewis, Phys. Rev. **95**, 83 (1954).
[6] B. Singh, Phys. Rev. **107**, 711 (1957).
[7] A. H. Compton and S. K. Allison, *X-rays in Theory and Experiment* (D. Van Nostrand Company, Princeton, 1935).

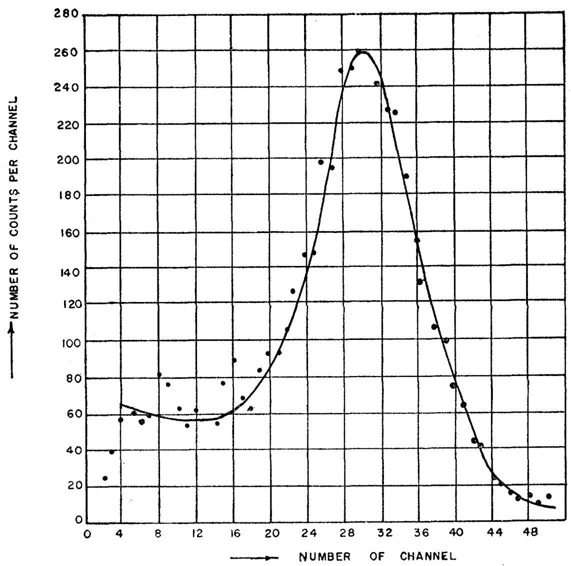

FIG. 1. Spectrum of 8.1-kev Cu K x-rays by accelerated charged particles. Attenuation of linear amplifier = 16 db. Pulse height analyzer bias = 12 volts.

voltage and the filling of the counter are kept the same in the two cases, the amplification of the linear amplifier is changed to 2.5 times that used in the case of Cu K x-rays, and the pulses are analyzed by a pulse height analyzer, then the pulses from both the sources should have their peaks approximately at the same place. The Cu K x-rays of 8.1 kev were analyzed by the fifty-channel pulse-height analyzer with an attenuation of 16 db, and the 3.24-kev L x-rays of Ag were analyzed with an attenuation of 8 db. It is found that the peaks of the differential distribution in the two cases are at about the same place. This indicates clearly that the x-rays examined are L x-rays of Ag (see Figs. 1 and 2).

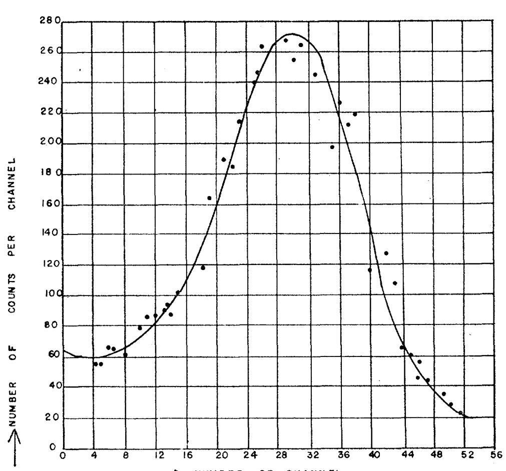

FIG. 2. Spectrum of 3.24-kev Ag L x-rays by accelerated charged particles. Attenuation of linear amplifier = 8 db. Pulse height analyzer bias = 12 volts.

The only difference is that the spread of the distribution of L x-rays of Ag is slightly more than that of K x-rays of Cu, which we should expect for lower energy.

2. Measurement of Mass Absorption Coefficient

In order to confirm the conclusion of the pulse-height comparison, a determination of the mass absorption coefficient of L x-rays of Ag in aluminum was made. The mass absorption coefficient of the x-rays examined was found to be 750 cm^2/g, which agrees with the value of Siegbahn[8] within the limit of the experimental errors.

IV. MEASUREMENT OF THE CROSS SECTIONS

A thin target of Ag, 0.5 mg/cm^2 thick, evaporated on spectroscopically pure aluminum backing (purity of Ag and Al $\approx$ 99.99%), is bombarded by accelerated

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

Element	Target thickness mg/cm^2	Energy of L x-rays kev	Incident particles	Energy of particles in Mev	Experimental cross section cm^2
$_{47}$Ag	0.5	3.24	protons	0.4	0.73×10^{-2}
				0.5	1.38×10^{-22}
				0.6	2.15×10^{-23}
				0.7	3.62×10^{-22}
				0.8	5.03×10^{-22}
				0.9	6.59×10^{-22}
				1.0	7.91×10^{-22}
			deuterons	0.4	1.11×10^{-22}
				0.5	2.67×10^{-23}
				0.6	5.15×10^{-23}
				0.7	8.75×10^{-23}
				0.8	$13.8\ \times10^{-23}$
			alpha particles	0.4	0.31×10^{-24}
				0.5	2.27×10^{-24}
				0.6	3.59×10^{-24}
				0.7	6.59×10^{-24}
				0.8	12.25×10^{-24}
				0.9	$21.2\ \times10^{-24}$
				1.0	30.97×10^{-24}
				1.1	50.58×10^{-24}

protons, deuterons, and alpha particles. Figure 2 shows a typical spectrum of L x-rays of Ag by accelerated particles.

To determine the cross section for the production of L x-rays from the target, the calculations described in a previous paper[6] are made. The angular distribution is assumed to be isotropic.[5]

The efficiency of the proportional counter filled with a mixture of 90% argon and 10% carbon dioxide to a pressure of 25 cm of Hg was 99.0±1% for the 3.24-kev x-rays. The cross section for the production of L x-rays of Ag, was finally corrected for the Auger transition, and the absolute cross section for L-shell ionization was determined. The fluorescent yield for L x-rays of Ag

[8] M. Siegbahn, *The Spectroscopy of X-rays* (Verlag Julius Springer, Berlin, 1925).

is equal to 0.1 according to Burhop.[9] The experimental results are given in Table I. Since L x-rays of Ag have an energy of 3.24 kev and as such a very large mass absorption coefficient, the largest source of error is the absorption in the target, in the chamber window, the counter window, etc. Careful analysis of these factors indicates that the accuracy of the measurements is $\pm 30\%$.

V. DISCUSSION AND CONCLUSIONS

The cross section for the L-shell ionization of Ag increases with increasing energy of the incident particles but the increase for protons is less rapid than that due to deuterons and alpha particles. Furthermore, for protons, the increase of the L-shell ionization cross section is less rapid than the K-shell ionization, and the cross section for the production of L x-rays is larger than that of K x-rays by a factor of 10^4. (For K x-rays, see Singh.[6]) A large cross section can be expected in consequence of the loose binding energy of electrons in L-shells.

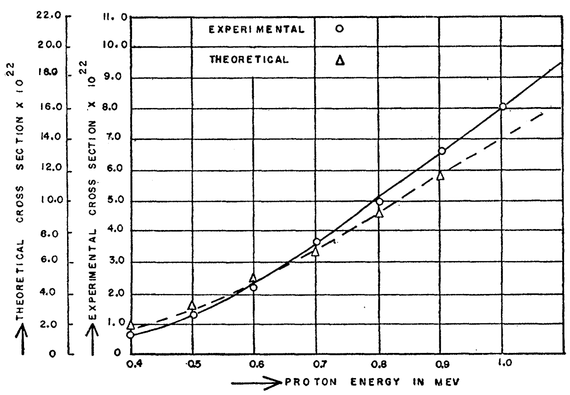

FIG. 3. Cross sections for L-shell ionization of Ag by protons.

The L-shell ionization cross sections for thick targets of four heavy elements, Ta, Au, Pb, and U have been measured by Bernstein and Lewis,[5] for protons of energy between 1.5 Mev and 4.25 Mev. In all cases, the cross section is found to increase with the increasing proton energy, but the increase is less rapid than the K-shell ionization measured by Lewis, Simmons, and Merzbacher.[10]

It is clear in our measurement that the cross section for the L-shell ionization of an element is much larger than that of the K-shell ionization of the same element for the same energy of the positively charged particles. It appears that the theory of Henneberg[11] for K-shell ionization can be used for L-shell ionization. Therefore, taking account of the excitation energy of the L electrons, the number of L electrons, and the radius of the L shell, the cross section for the L-shell ionization is given by

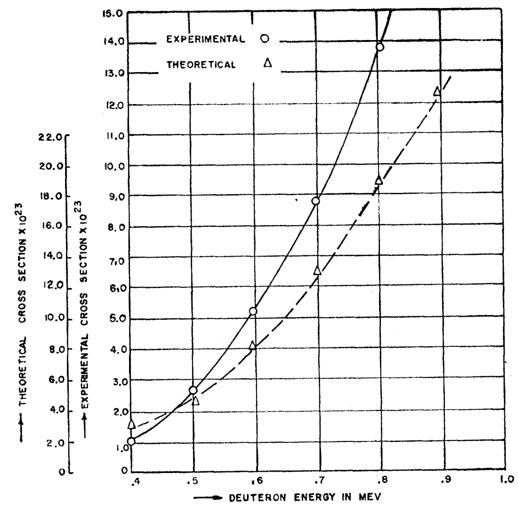

FIG. 4. Cross sections for L-shell ionization of Ag by deuterons.

$$\sigma_L(\mathrm{cm}^2) = (Z')^2 \times \frac{N_L}{N_K}\left(\frac{n_2}{n_1}\right)^4 \times \frac{3.51\times 10^{-16}}{(Z-2)^4\theta} \times \Phi_0(\eta'),$$

where $\Phi_0(\eta')$ is the same as that for K-shell ionization used by Henneberg[11] except that the excitation energy of the L shell is used in place of the K-shell excitation energy. Here Z' = the charge on the incident particles, N_L = the number of electrons in the L shell, N_K = the number of electrons in the K shell, n_2 = the total quantum number for the L shell, n_1 = the total quantum number for the K shell, and θ = the outer screening

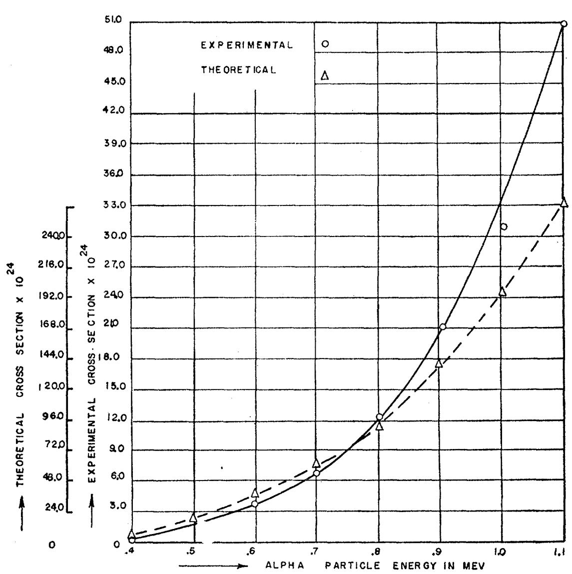

FIG. 5. Cross sections for L-shell ionization of Ag by alpha particles.

[9] E. H. S. Burhop, *The Auger Effect and Other Radiationless Transitions* (Cambridge University Press, Cambridge, 1952), p. 55.

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

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

factor, $(Z-2)$ is used in place of Z (atomic number of target element) because of the inner screening effect of the K electrons.

According to this formula, the cross section for the L-shell ionization depends upon two main factors. The first is an exponential function of the energy and the second is proportional to the fourth power of the energy. At lower energies the exponential factor is small and the cross section is proportional to the fourth power of energy. At higher energies the exponential factor becomes appreciable. The theoretical cross sections obtained by the use of this formula are compared with the experimental cross sections for L-shell ionization of Ag by protons, deuterons, and alpha particles and are shown in Figs. 3, 4, and 5. Here we have used the value of θ applicable to K-shell ionization and there is a general agreement as far as an increase of the cross section with increasing energy of the incident particles is concerned. However, if θ is taken equal to unity, which means no outer screening, there is better agreement. For protons and deuterons the experimental cross section is smaller than the theoretical cross section by a factor of two to three, but in the case of alpha particles the discrepancy is much greater, as with K-shell ionization. Therefore the systematic difference between the theoretical and experimental cross sections of K-shell and L-shell ionization of elements suggests that a more exact theoretical treatment at low energies might bring theory and experiment into closer agreement.

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