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K-Shell Ionization of Ag, Sn, and Au from Electron Bombardment

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Cross sections for K-shell ionization have been measured at electron bombarding energies of 0.10, 0.15, 0.20, 0.25, 0.30, and 1.00 MeV for Ag, and of 0.20, 0.60, 0.80, 1.00, 1.20, 1.40, 1.70, and 2.00 MeV for Sn and Au. Below 0.50 MeV, the results for Ag are in excellent agreement with the relativistic calculations of Arthurs and Moiseiwitsch. For Sn at 0.20 and 0.60 MeV, where the theoretical values are available, the experimental cross sections are also in very close agreement. Although the experimental cross section for Au at 0.20 MeV is very nearly the same as the calculated result of Arthurs and Moiseiwitsch at this energy, at 0.60 MeV and higher electron energies the experimental results for Au are, on the average, about 15% lower than the values of Arthurs and Moiseiwitsch.

INTRODUCTION

A RECENT article by Motz and Placious[1] reported cross-section measurements for K-shell ionization of Sn and Au by electron bombardment. The measurements of Motz and Placious on Sn at 0.05, 0.10, and 0.50 MeV and on Au at 0.10, 0.20, and 0.50 MeV were presented along with a survey of most of the previously reported experimental studies. The cross sections measured by Motz and Placious are in reasonably good agreement with the relativistic calculations of Arthurs and Moiseiwitsch (AM).[2] The earlier experimental work on K-shell ionization summarized in the article indicated that the previous work had been confined to the region of the periodic chart below Sn ($Z=50$). The agreement with the theory of Arthurs and Moiseiwitsch obtained by Motz and Placious resulted in an inconsistency in the overall comparison of the experiments to the theory. K-shell ionization cross-section measurements on Ni ($Z=28$) were in excellent agreement with the theory, as were those of Motz and Placious for Sn ($Z=50$). However, measurements on Ag ($Z=47$) had been reported earlier, yielding K-shell ionization cross sections lower than those calculated by Arthurs and Moiseiwitsch by about 20% and in fact they appeared to be in better agreement with the nonrelativistic theory of Burhop.[3]

The present paper reports measurements of K-shell ionization cross sections for Sn and Au, overlapping the measurements of Motz and Placious and extending up to 2.0 MeV. In addition, measurements of K-shell ionization cross sections for Ag have been made at 0.10, 0.15, 0.20, 0.25, 0.30, and 1.0 MeV. The present measurements indicate very good agreement with the theory of Arthurs and Moiseiwitsch at the lower energies for Ag where the values are available for comparison, in contrast to the previously reported measurements. At 1.0 MeV the theoretical value is not available. The experimental cross sections for Au are 15% lower than the values of Arthurs and Moiseiwitsch at all energies above 200 keV.

EXPERIMENTAL PROCEDURE

Pulse-height distributions, from which the K x-ray line intensities were reduced, were accumulated with two experimental arrangements. For incident electron kinetic energies less than 0.30 MeV a TNC Cockcroft-Walton accelerator provided the source of monoenergetic electrons. The detector in this case was a 2×2-in. NaI(Tl) crystal scintillation detector. The entrance window of the crystal was a 0.003-in. aluminum foil. The detector viewed thin targets of the materials of interest through a 0.005-in. Mylar window in a cylindrical aluminum scattering chamber. The detector crystal was positioned 12 in. from the target with an intervening air path of 7 in. Thus for the lowest energy line measured, namely the 23-keV Ag line, the attenua-

[1] J. W. Motz and R. C. Placious, Phys. Rev. **135**, A662 (1964).
[2] A. M. Arthurs and B. L. Moiseiwitsch, Proc. Roy. Soc. (London) **A247**, 550 (1958).
[3] E. H. S. Burhop, Proc. Cambridge Phil. Soc. **36**, 43 (1940).

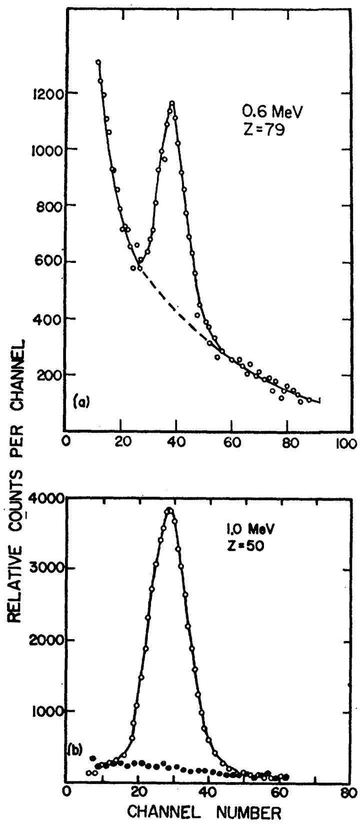

FIG. 1. Pulse-height distributions resulting from the K x rays from Sn and Au, obtained with the anticoincidence spectrometer. Both spectra were taken with the scintillation spectrometer at 135 deg with respect to the incident electron-beam direction. For the Au spectrum (a), the energy of the incident electrons was 0.60 MeV. The Sn spectrum (b) was obtained at 1.0-MeV bombarding energy. In this case the lower curve, which appears in the region of the x-ray peak (25.8 keV), is the continuous bremsstrahlung spectrum from Al, normalized to the continuous background for Sn.

tion of the x-ray beam was only 6%. For incident electron kinetic energies above 0.30 MeV, a Van de Graaff accelerator provided the beam of electrons. In this case a Trail and Raboy[4] detector was used with a 2.32×6-in. NaI(Tl) center crystal and a 12-in.-diam NaI(Tl) anticoincidence annulus. The entrance window of the center crystal was 0.005 in. of aluminum and 0.005 in. of aluminum oxide. The scattering chamber was also provided with a 0.005-in. Mylar window. The distance in air from the detector to the window was 34 in. Total attenuation of the K x-ray beam for the lowest energy line amounted to 13%.

For both experimental arrangements the NaI(Tl) crystals used in the measurements far exceeded the size required for efficient detection of the K x-ray lines. However, since the background spectrum consists almost entirely of the incident-electron bremsstrahlung spectrum, it cannot be decreased in the region of the lines by reducing the crystal size. Furthermore, an accurate measurement of the bremsstrahlung spectrum, which extends in energy out to the incident electron kinetic energy, allows it to be removed accurately in the region of the K x ray, since the shape of the continuous spectrum is well known. This method of removing the bremsstrahlung background is illustrated in Fig. 1, which gives typical pulse-height distributions produced in the anticoincidence spectrometer at 1-MeV bombarding energy. In the case of Sn ($Z=50$), which is shown in Fig. 1(b), the lower curve in the region of the K x-ray peak at 25.8 keV is the experimental continuous bremsstrahlung spectrum from aluminum, normalized to the continuous background for Sn. The energy of the Al K x ray is 1.4 keV, well below the low-energy cutoff of the spectrum shown. The angle of observation of the K x-ray spectra in these measurements was 120 deg with respect to the incident electron beam.

Self-supporting targets of Ag, Sn, and Au were made by vacuum evaporation onto glass slides from which they were removed by floating off in water. The thicknesses of the foils were determined by weighing known areas of the materials cut from the targets after the measurements had been completed. Thicknesses determined in this manner were verified by measuring electron yields due to Coulomb scattering into a known geometry. At 200 keV the thinnest Sn and Au targets used were prepared by evaporation onto VYNS backings. Measurements were repeated on several different targets in some cases, with good agreement obtained between the various measurements.

Energy calibrations of the accelerators were carried out by observing with a lithium-ion-drift silicon detector the peak from the Coulomb scattering of the incident electrons by the target foils. The lithium-ion-drift silicon detector was calibrated by measurements of the internal-conversion-electron lines of a Th($B+C+C''$) source at 0.148 and 0.222 MeV, a Cs^{137} source at 0.625 MeV, and a Bi^{207} source at 0.972 and 1.68 MeV.

The observed x-ray yields were corrected for K-shell fluorescence yield by using the values 0.80 for Ag, 0.84 for Sn, and 0.95 for Au, from Wapstra *et al.*[5] No corrections were made for an angular dependence of the x-ray yields, as the K x-ray emission has been found to be isotropic.[1]

TABLE I. K-shell ionization cross sections.

Electron energy (MeV)	Ag ($Z=47$) Expt.	Ag ($Z=47$) Theor. (AM)	σ_K (barns) Sn ($Z=50$) Expt.	Sn ($Z=50$) Theor. (AM)	Au ($Z=79$) Expt.	Au ($Z=79$) Theor. (AM)
0.10	59±6	59.0				
0.15	59±6	59.5				
0.20	52±5	54.5	47+5	47.4	8.7±1	8.4
0.25	52±5	51.0				
0.30	49±5	49.3				
0.60			40±4	38.2	10±1	11.5
0.80			39±4		10±1	11.8
1.00	47±5		39±4		10±1	12.1
1.20			40±4		10±1	12.3
1.40			42±4		10±1	12.5
1.70			43±4		11±1	12.6
2.00			44±4		11±1	12.8

[4] C. C. Trail and S. Raboy, Rev. Sci. Instr. **30**, 425 (1959).

[5] A. H. Wapstra, G. I. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 82.

Experimental error in determining the cross sections due to errors in electron-current integration, target thicknesses, background removal, and correction for x-ray attenuation is estimated to be $\pm 10\%$.

DISCUSSION OF RESULTS

The experimental *K*-shell ionization cross sections from the present measurements are given in Table I for Ag, Sn, and Au. A comparison of these values and the previously reported experimental values with the theory of Arthurs and Moiseiwitsch is shown in Fig. 2. The present experimental data are represented by open circles; previous data are shown as solid circles, and the theory of Arthurs and Moiseiwitsch is shown as a solid line. As indicated in Fig. 2(a) the measurements for Sn join smoothly with the values reported by Motz and Placious. At 0.20 MeV the value of Motz and Placious is almost the same as the presently reported value. Their value at 0.50 MeV is in line with the next value reported from the present measurements at 0.60 MeV and with the values at higher energies. The agreement with the theoretical values of Arthurs and Moiseiwitsch is well within the accuracy of the experiments. Also in Fig. 2(a) the *K*-shell ionization-cross-section values for Au of the present experiment are shown with those of Motz and Placious, but the values from the two experiments, while within the reported experimental accuracies for the measurements, are not in as good agreement as for the case of Sn. At 0.20 MeV the present measurement is about 10% below the value reported by Motz and Placious, and their value at 0.50 MeV appears to be about 10% above the trend of the present measurements. However, below 0.50 MeV the experimental values are predicted by the theory of Arthurs and Moiseiwitsch to within the accuracy of the measurements. Above 0.50 MeV the present experimental data are below the theoretical predictions by an average of 15%. The dashed line is the theory of Perlman[6] for Hg ($Z=80$), as given by Motz and Placious. As pointed out by Motz and Placious[1], this theory should give the most accurate cross-section values. Since the present measurements for Au are 10% below the measurements of Motz and Placious, the present cross section values are closer to the predictions of Perlman than the previously reported values. The present experimental value at 0.60 MeV appears to be close to the value obtained from the theory of Perlman for Hg and corrected for the Z dependence by a factor derived from the relative cross-section values from the theory of Arthurs and Moiseiwitsch.

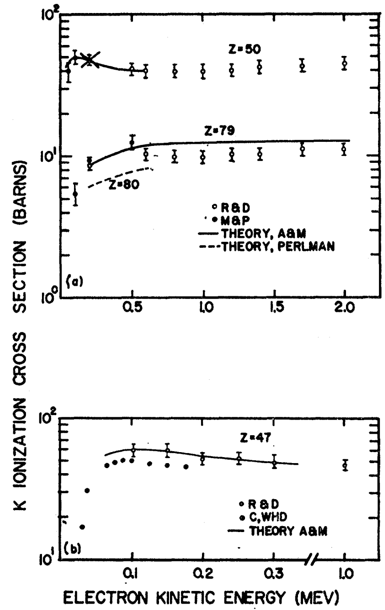

FIG. 2. Dependence of the *K*-ionization cross section for Ag, Sn, and Au on the incident electron kinetic energy. The open circles represent the present experimental data; the solid circles show previously reported experimental data; and the solid lines give the theoretical cross sections calculated by Arthurs and Moiseiwitsch (Ref. 2). The dashed curve in (a) represents values calculated for $Z=80$ from the theory of Perlman. The previously reported experimental data shown in (a) are those of Motz and Placious (Ref. 1). The $\times$ at 0.20 MeV indicates that the present experimental cross-section value is nearly identical to the result reported by Motz and Placious at that energy. The data on Ag in (b) are from Clark (Ref. 6) and Webster *et al.* (Ref. 7).

In Fig. 2(b) a comparison of the present *K*-shell ionization-cross-section values for Ag ($Z=47$) to the theory of Arthurs and Moiseiwitsch and to the previous measurements of Clark[6] and of Webster *et al.*[7] is shown. The present experimental values are in good agreement with the theory as would be expected on the basis of the agreement between the theory and experiment for Sn ($Z=50$). This is in contrast to the previously reported measurements which are 20% below the theory. It is felt that the accuracy of the present measurements would rule out the possibility of a real disagreement of this magnitude between the experiment and theory.

[6] J. C. Clark, Phys. Rev. 48, 30 (1935).

[7] D. L. Webster, W. W. Hansen, and F. B. Duveneck, Phys. Rev. 43, 851 (1933).