PHYSICAL REVIEW LETTERS

VOLUME 31 | 1 OCTOBER 1973 | NUMBER 14

Differential Cross Section for K-Shell Ionization of Copper and Silver by Electron Bombardment

C. A. Quarles and J. D. Faulk
Texas Christian University, Fort Worth, Texas 76129
(Received 24 July 1973)

In a coincidence experiment, we have measured the absolute differential cross section for K-shell ionization of Cu and Ag by 140-keV electrons. The results are discussed and compared with the calculations of Das and of Cooper and Kalbensvedt. While the agreement between experiment and theory is reasonable at 15°, there appears to be a sizable discrepancy at 45°, particularly at larger detected electron energy.

We report here the first measurements of the differential cross section for K-shell ionization by electron bombardment of thin metallic film targets of Cu and Ag. The production of a K-shell vacancy is followed with known probability by the emission of a characteristic K x ray. We have utilized this fact to measure the cross section differential in electron energy and angle by observing either the scattered or the ejected electron in coincidence with the x ray. We have not observed the second electron and, hence, the present experiment measures a cross section which has been integrated over this second electron.

These measurements of inner-shell ionization cross sections are important in the attempt to understand better the basic inelastic electron-atom interaction of ionization. Heretofore, measurements of K-shell ionization of targets of intermediate atomic number by electron bombardment at moderately relativistic energy have consisted of total-cross-section measurements where only the characteristic K x ray was observed.[1] For low atomic number ($Z \leq 13$) and correspondingly low electron energy, there is a variety of data. Total-cross-section measurements have been made by observing the Auger electron[2] as well as the x ray[3]; total backscattering cross sections have been measured by observing the energy loss of the scattered electron[4]; and recently a measurement has been reported of the fully differential cross section for K-shell ionization of carbon in which both the scattered and ejected electron were observed.[5] It would also be interesting to have such data for higher energy and higher atomic number; in the meantime, however, the results presented here provide much more detailed information than has previously been available in this region.

Beginning with the work of Burhop in 1940, several attempts[6] have been made over the years to describe the total K-shell ionization cross section, but these have been only moderately successful.

The differential cross section has recently been considered by several authors. Glassgold and Ialongo[7] have calculated the fully differential cross section in a nonrelativistic approximation, but their work is not directly applicable to the present experiment. Cooper and Kolbensvedt[8] have extended the earlier work of Ford and Mullin[9] and Weber, Deck, and Mullin[10] and calculated the cross section differential in the detected electron angle and energy. Their work includes exchange and interference effects, but is expected to be applicable mainly at large momentum transfer and when neither electron has too low an energy. Das[11] has also extended the earlier work of Weber, Deck, and Mullin, and calculated the spectrum for the low-energy ejected electron in the extreme relativistic case. As part of an attempt to obtain a better total cross section, Das[12] has also calculated the differential cross section for the scattered electron in the Born approximation using the Ochkur approximation to include the exchange term. The calculation uses the relativistic interaction Hamiltonian, nonrelativistic hydrogenic wave functions for the K-shell electron, Coulomb wave functions for the low-energy (ejected) electron, and relativistic plane waves for the incident and high-energy (scattered) electron. Fleming[13] has independently done a calculation similar to that of Das using the semirelativistic Darwin wave functions for the K-shell electron, and his results agree with those of Das to a few percent for Cu and Ag.

In the present experiment, electrons were accelerated to kinetic energy 140 keV and struck a thin self-supporting target of Cu or Ag ($\simeq 50$ $\mu g/cm^2$ thickness) placed at the center of a scattering chamber. Electrons scattered at 15 (or 45) deg with respect to the incident beam were momentum analyzed in a small magnetic spectrometer and detected by a silicon surface barrier detector. Characteristic K x rays produced at 90° with respect to the incident electron beam passed out of the scattering chamber through a thin Mylar window and were detected by a Ge(Li) x-ray detector. A fast-slow coincidence system with a timing resolution of $\simeq 20$ nsec was used to measure the coincidence rate between the x rays and the scattered electrons. The differential cross section for K-shell ionization was then determined from

$$\frac{d\sigma}{d\Omega\, dE}=\frac{4\pi N_c}{N_0 \tau \epsilon\, \Delta\Omega\, \Delta E\, \epsilon_\gamma\, \Delta\Omega_\gamma\, \omega_K},$$

where N_c is the number of coincidences, N_0 the incident electron beam rate, τ the target thickness, $\Delta\Omega$ the electron solid angle, ϵ the efficiency of the electron detector–magnetic spectrometer, ΔE the energy width, $\Delta\Omega_\gamma$ the photon detector solid angle, ϵ_γ the photon detector efficiency, and ω_K the K-shell fluorescent yield of the target atom.

In an attempt to minimize the experimental errors, several of the above factors were determined in combination. The factor $\tau\epsilon\,\Delta\Omega\,\Delta E$ was determined directly by measuring the number of electrons elastically scattered into the magnetic spectrometer as a function of incident beam energy. The resulting transmission curve was normalized to the elastic-scattering cross-section calculation of Doggett and Spencer[14] for Cu and Sherman[15] for Ag (Sherman's results for Cd were adjusted for Z^2 dependence), and integrated over energy to obtain the above factor. The energy width of the transmission curve was typically of the order of 20-keV full width at half-maximum. The factor $\epsilon_\gamma\,\Delta\Omega_\gamma/4\pi$ was measured directly using calibrated radioactive sources placed at the position of the target. The fluorescent yields of 0.443 for Cu and 0.834 for Ag were taken from the compilation of Bambynek *et al.*[16] A more complete description of the details of the experiment will be published later.

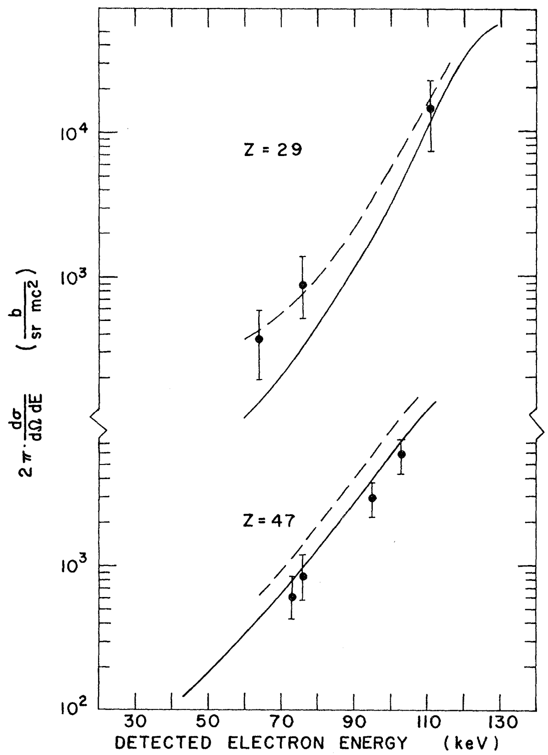

FIG. 1. Differential K-shell ionization cross section at 15° for Cu and Ag versus detected electron energy for incident electrons of 140 keV energy. Solid line, calculation of Das; dashed line, Das calculation corrected for electron spectrometer transmission.

The results of the experiment are shown in Fig. 1 for the electron detected at an angle of 15°, and in Fig. 2 for the electron angle at 45°. We have plotted $2\pi\, d\sigma/d\Omega\, dE$ versus the average detected electron energy. The errors shown are a com-

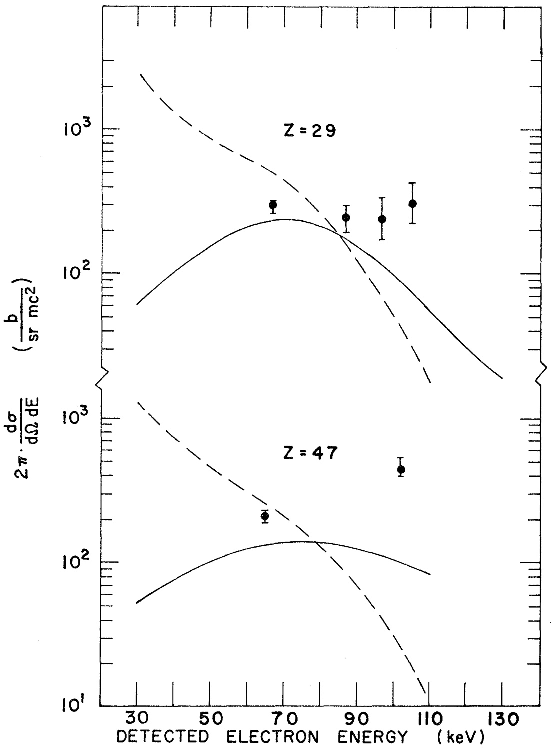

FIG. 2. Differential K-shell ionization cross section at 45° for Cu and Ag versus detected electron energy for incident electrons of 140 keV energy. Solid line, calculation of Das for scattered electrons; dashed line, calculation of Cooper and Kolbensvedt.

bination of statistical error and error due to uncertainty in the absolute scattering angle and the position of the target. This angular error ranged from negligible at 45° and 65 keV for Ag to about 50% at 15° and 70 keV for Cu. The statistical error ranged from about 6% to 35%. In addition there is a systematic error of about 10% due to uncertainty in the transmission of the spectrometer, the photon detector efficiency, and the beam current.

For the case of electrons detected at 15° with respect to the incident beam, we have evaluated the cross-section formula of Das, Eq. (9) of Ref. 12, for the scattered electron. This is shown as the solid line in Fig. 1. Because of the broad ($\simeq$20 keV) energy resolution of the magnetic spectrometer, it is necessary to integrate the theoretical cross section over the measured transmission curve for the spectrometer in order to obtain a theoretical value which can be directly compared with the experimental points. This has been done and the result is shown as the dashed line in Fig. 1. The correction is larger for Cu than for Ag because of a high-energy tail in the spectrometer transmission function coupled with the fact that the scattered electron energy allowed for Cu extends an additional 16.5 keV beyond that allowed for Ag. Considering both the errors and the fact that this experiment represents the first data available for comparison with theory, the agreement between the experiment and the theory at 15° is generally good, although the theory does appear to overestimate the measured cross section somewhat, particularly for Ag. The neglect of a full relativistic treatment for the K-shell electrons of Ag may be a problem. However, as mentioned above, the use of Darwin wave functions does not change the theory significantly for Ag, so perhaps an even more relativistic treatment may be necessary. The neglect of the inclusion of the ejected electron would not appear to be significant at 15° and, in any case, its inclusion would tend to raise the theoretical value. Clearly, to resolve any possible discrepancies at the forward angles will require more precise data, and experimental effort in this direction is continuing.

The comparison of the data with the theoretical predictions for the case of the electron detected at 45°, shown in Fig. 2, presents a much more difficult problem. Again we have plotted the cross-section formula of Das for the scattered electron alone as the solid curve. Unlike the case at 15°, the correction to the theoretical curve for spectrometer transmission at 45° is less than a few percent at the two energies of interest so only the uncorrected curves are shown for comparison. The dashed curve is an evaluation of the cross-section formula for the detected electron of Cooper and Kolbensvedt, Eq. (15) of Ref. 8. This formula may be expected to be valid for 65 keV detected electron energy, but it is surely not valid for either the high or low energies because Coulomb wave functions were not used to describe the low-energy electron. Hence, as expected, the formula of Cooper and Kolbensvedt grossly underestimates the measured value at 100 keV. At 65 keV, the agreement between this formula and the experiment is rather good for Ag, while for Cu the theory is higher than the measured cross section by a factor of about 1.7.

The formula for the scattered electron of Das underestimates the cross section at both 65 and 100 keV. This is to be expected since the experiment detects both electrons scattered and ejected at 45° with the measured energy, whereas the theory only considers the scattered electrons.

Das's calculation for the ejected electron spectrum for the case of extreme relativistic incident energy is not applicable at the energies of this experiment. Hence, it is not possible as yet to say whether the particularly large discrepancy at 100 keV is completely due to the neglect of the ejected electron contribution. However, since the difference between the calculation of Cooper and Kolbensvedt and that of Das may be a reasonable estimate of the ejected electron spectrum at 65 keV, it is difficult to see how the ejected electron contribution could exceed the scattered electron contribution to the extent needed at 100 keV to bring the theory and the experiment into good agreement. Incidently, since the case at 100 keV represents the point of largest momentum transfer from the incident to the detected electron observed in the experiment, it is reasonable to assume that further discrepancies may occur particularly where both the momentum transfer and the energy of one electron are large. Since the cross section is strongly angular dependent, we have investigated whether this discrepancy at 100 keV could be due to the finite angular resolution of the spectrometer. In order to bring the expected theoretical cross section up to the measured value at 100 keV, however, would require a predominant contribution of electrons which scattered through angles more than 10° less than that allowed by the angular width (± 2°) of the system. Hence, we do not believe this to be the source of the observed discrepancy.

To resolve the apparent discrepancies, more experimental and theoretical work is needed. Clearly, a calculation of the ejected electron contribution valid in this energy range or the inclusion of Coulomb wave corrections in the detected electron cross-section formula of Cooper and Kolbensvedt would be useful. Further experiments are in progress at larger momentum transfer, and efforts are underway to reduce further the possible experimental errors.

In conclusion, we have presented the first results for the differential cross section for K-shell ionization of Cu and Ag by 140-keV electrons. The results are in reasonable agreement with the expected cross section for the scattered electron at 15°, but significant discrepancies appear to exist between the experiment and the available theories at 45°.

We would like to acknowledge the assistance of Mr. R. Solanki and Mr. J. Altman in taking data.

[1]D. V. Davis *et al.*, Phys. Lett. 38A, 169 (1972), and references cited therein.

[2]G. Glupe and W. Melhorn, Phys. Lett. 25A, 274 (1967).

[3]W. Hink *et al.*, Z. Phys. 226, 222 (1969), and 244, 140 (1971).

[4]R. L. Gerlach and A. R. DuCharme, Phys. Rev. A 6, 1892 (1972).

[5]R. Camilloni *et al.*, Phys. Rev. Lett. 29, 618 (1972).

[6]E. H. S. Burhop, Proc. Cambridge Phil. Soc. 36, 43 (1940), and references cited in Ref. 1.

[7]A. E. Glassgold and G. Ialongo, Phys. Rev. 175, 151 (1968), and 186, 266 (1969).

[8]J. W. Cooper and H. Kolbensvedt, Phys. Rev. A 5, 677 (1972).

[9]G. W. Ford and C. J. Mullin, Phys. Rev. 110, 520 (1958).

[10]T. A. Weber, R. T. Deck, and C. J. Mullin, Phys. Rev. 130, 660 (1963).

[11]J. N. Das, Phys. Rev. A 4, 1025 (1971).

[12]J. N. Das, Nuovo Cimento 12B, 197 (1972).

[13]R. G. Fleming, Ph.D. dissertation, Texas Christian University, 1972 (unpublished).

[14]J. A. Doggett and L. V. Spencer, Phys. Rev. 103, 1597 (1956).

[15]N. Sherman, Phys. Rev. 103, 1601 (1956).

[16]W. Bambynek *et al.*, Rev. Mod. Phys. 44, 716 (1972).