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Cross sections for $L_{2,3}$ Auger emission in 22- to 300-keV H^+ + Ar collisions*

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INTRODUCTION

Measurements of inner-shell ionization cross sections due to ion bombardment are usually made by measuring the x-ray yield from solid targets. These measurements are subject to uncertainties of various kinds as discussed by Taulbjerg *et al.*[1] and by Kessel and Fastrup.[2] For low-Z targets there is the additional large uncertainty as a result of lack of knowledge of the fluorescence yields. In recent years it has been shown that values of fluorescence yields depend strongly on the accompanying outer-shell ionization and therefore on the type of projectile which caused the inner-shell-vacancy state under study. Since these yields may differ by as much as an order of magnitude from those measured or calculated for pure vacancy states, ionization cross sections determined from x-ray data are not very accurate. For low-Z targets the Auger yield is close to 100% and therefore is not a factor in the calculation of ionization cross sections from Auger cross sections.

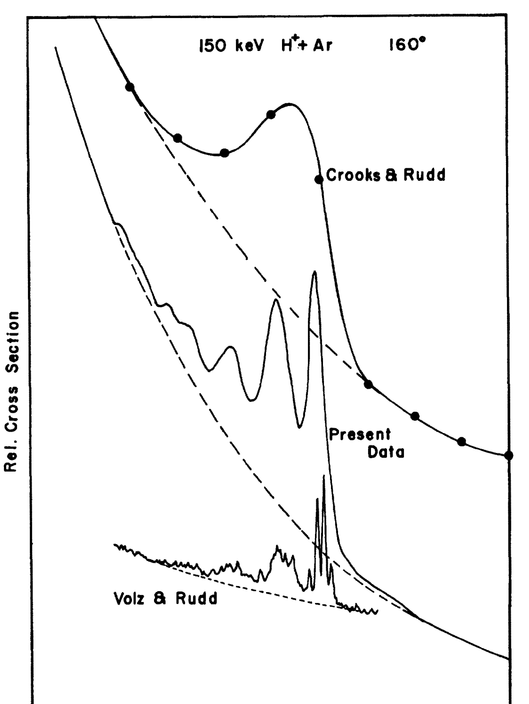

FIG. 1. Typical runs over the $L_{2,3}$ Auger spectrum of argon with 150-keV proton impact. Electrons detected at 160° from the beam direction. Top curve, data from Crooks and Rudd (Ref. 8) taken at 5.7% (11 eV) analyzer resolution. Center curve, present results taken at 1.8% (3.4 eV) resolution. Bottom curve, data from Volz and Rudd (Ref. 6) at 0.9-eV resolution. Dashed lines represent estimates of the background continuum cross sections extrapolated from the regions above and below the Auger region.

Although a few K-Auger cross-section measurements have been made[3-5] using proton impact, very few L-Auger data are available. Volz and Rudd[6] gave data for excitation of specific Auger lines in argon, and recently Stolterfoht, Schneider, and Ziem[7] made L-Auger measurements in argon from 50 to 600 keV. In the present paper measurements of $L_{2,3}$ Auger cross sections for $H^+ +$ Ar collisions from 22 to 150 keV are presented. Both total cross sections and cross sections differential in angle of electron ejection were made. In addition, data from two earlier projects at this laboratory[6,8] with different objectives were analyzed to obtain additional cross sections from 50 to 300 keV. The total cross sections are compared with the binary-encounter calculations of Garcia.[9,10]

MEASUREMENTS

Figure 1 shows selected runs from the present data and from previously published work of Volz and Rudd[6] and Crooks and Rudd.[8] While they were taken at quite different energy resolutions and for different purposes, they can all yield both differential and total Auger cross sections. Only in the Crooks work were the cross sections measured on an absolute basis. In Volz's thesis[11] the cross sections were normalized to some unpublished work from this laboratory which was later found to be incorrect. When Volz's work was published,[6] the data were renormalized to the preliminary results of Crooks. The final results of Crooks[8] contained additional corrections which make Volz's published cross sections too low by about 20%. Additionally, since Volz's spectra were taken at high resolution, individual lines were measured and cross sections only for the sum of the diagram lines were presented. In this paper the entire area under the Auger region was measured, thus including all the satellite lines. Each run was normalized to the Crooks published continuum data at 150 and 219 eV.

The apparatus used for the present data was the same as in earlier work.[6,12,13] Briefly, a magnetically analyzed ion beam enters a collision chamber containing the target gas. The beam is caught in a Faraday cup and the current measured. The current was steady enough in this work that the divider used to compensate for fluctuations[13] was not needed. Electrons ejected in a given direction from a short section of beam were energy analyzed by a parallel-plate electrostatic analyzer and counted by an electron-multiplier detector. The output of a count-rate meter was displayed on an X-Y recorder as a function of the analyzer potential. Most of the data were taken at an electron ejection angle of 90° but some runs were made at 30° and 160°.

Since the Auger cross section is a rapidly varying function of proton impact energy in this region, it is necessary to know the energy scale accurately. The accelerator terminal voltage was measured with a voltage divider and differential voltmeter combination which was calibrated within $\frac{1}{4}$%. In addition, account was taken of the fact that the protons are created in the rf ion source at a potential above that of the high-voltage terminal by an amount practically equal to the extraction potential. Measurements with a cylindrical electrostatic analyzer in the beam path confirm this and therefore the extraction voltage (typically 2000–4000 V) was added to the terminal potential to find the energy of the beam.

Below 100 keV the neutralization of the beam by the target gas became appreciable and necessitated a correction which became increasingly larger the lower the impact energy. This was partly because the neutralization cross section is large at low energies but also because the target gas pressure which was typically 1–1.5 mTorr above 50 keV was raised to 2.5–3 mTorr at 30 keV and lower to produce a usable count rate.

The major source of uncertainty in Auger cross-section measurements is in estimating the contribution of the background continuum in the Auger region. To do this it is necessary to extrapolate from the continuum above and below the Auger region. In this work these base lines were simply drawn by eye as shown on Fig. 1. Because the shape of the continuum changes with angle and projectile energy, more systematic methods of drawing the line would probably not increase the accuracy greatly.

RESULTS

Figure 2 shows that the angular distributions obtained for 50–300 keV are isotropic within the error bars which are ± 30% except at the smaller angles where they are 50% because of the poorer Auger-to-continuum ratio. Previously, Volz and Rudd[6] showed that four specific Auger diagram lines were isotropic within 15%. However, Cleff and Mehlhorn[14] made measurements of the intensity of the L_3-$M_{2,3}$ (^1S) line in the argon spectrum relative to one which is known to be isotropic on theoretical grounds and found a small (< 10%) anisotropy using electron excitation. The Volz data were studied in the same way for 300-keV

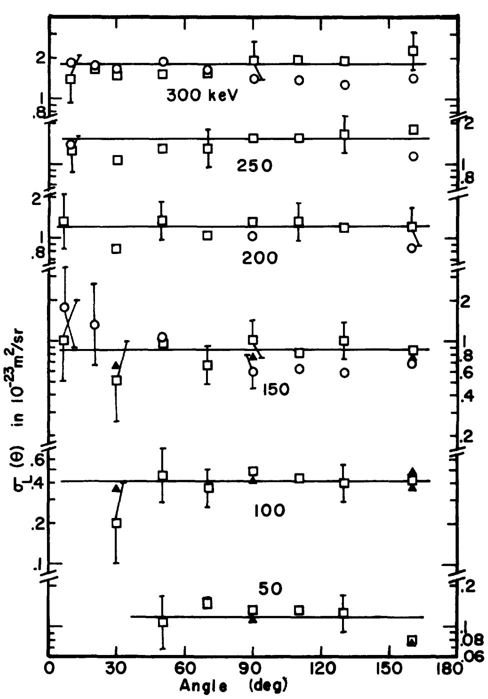

FIG. 2. Angular distributions of the $L_{2,3}$ Auger cross sections in $H^+ + Ar$ collisions at energies from 50 to 300 keV. Open squares, data from Crooks and Rudd (Ref. 8). Open circles, data from Volz and Rudd (Ref 6). Open triangles, present data.

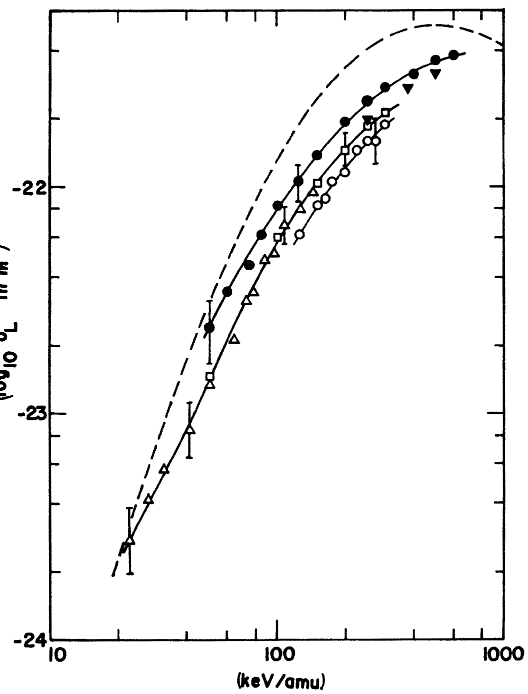

FIG. 3. Total $L_{2,3}$ Auger cross sections in H^+ (or D^+) + Ar collisions. Open squares, data from Crooks and Rudd (Ref. 8); open circles, data from Volz and Rudd (Ref. 6); open triangles, present data; solid circles, data from Stolterfoht *et al*. (Ref. 7); inverted solid triangles, D^+ + Ar data from Watson and Toburen (Ref. 4); dashed line, binary-encounter calculation of Garcia (Refs. 9 and 10).

proton impact and no anisotropy larger than 10% could be found. Stolterfoht, Schneider, and Ziem[7] obtained the same result.

Assuming an isotropic distribution of ejected Auger electrons, the total Auger cross sections can be calculated from measurements at any one angle. Such calculations were made for all the combinations of angle and projectile energy and were weighted according to their estimated accuracy and reliability to obtain final average values for each proton energy. The results are shown in Fig. 3. The low value of the Volz data probably results from the difficulty in drawing the continuum lines since his data did not extend much beyond the Auger region. The present data agree well with cross scetions determined from the Crooks data and a single line is drawn through both sets. This line is lower than the results of Ref. 7 by a factor of 0.6–0.75. This discrepancy is difficult to understand since the continuum cross sections of Ref. 7 agreed well with those of Crooks above 100 keV. Nevertheless, the combined error bars of 40–70% allow us to say that the Auger cross sections measured at Berlin and Nebraska do agree. Watson and Toburen[4] have presented data for deuterons on argon (also shown in Fig. 3) which agree well with the present results at 250 keV/amu.

Calculations were made on the binary-encounter theory by scaling the results of Garcia[9,10] to the L_1 and $L_{2,3}$ shells of argon. Since nearly all of the L_1 vacancies lead to $L_{2,3}$ vacancies through Coster-Kronig transitions the cross sections for L_1 shell ionization have to be added to those for the $L_{2,3}$ shell to obtain results which may be compared with the measurements. The calculated cross sections are larger than the present results and the Crooks data by a factor of 2 from 30 to 300 keV.

Very recently Brandt and Lapicki[15] have corrected the plane-wave Born-approximation cross sections for this process by taking account of the binding and Coulomb-deflection effects and obtain results much closer to the experimental values. They lie midway between the data of Ref. 7 and our data above 100 keV and agree very well with our data below 50 keV.

DISCUSSION OF ERRORS

The Crooks data are assigned an uncertainty of 19% which results chiefly from the 16% uncertainty in the absolute value of his double differential cross sections. Errors in estimating continua and measuring Auger areas are reduced by averaging over measurements at eight different angles. The uncertainty in the cross sections derived from Volz's data is estimated to be 25% which includes a 15% systematic error in drawing the continuum lines. In the present data the 16% uncertainty in the Crooks data appears in the normalization process. The beam neutralization at low energies becomes important, as noted, and results in an uncertainty in the correction factor which varies from 4% at 100 keV to 33% at 22 keV. The over-all uncertainty ranges from 23% to 40%. Some representative error bars are drawn in Fig. 3.

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