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K-Auger emission from carbon foils for 1-MeV-proton impact

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The spectra of secondary electrons emitted from carbon foils have been measured for excitation by 1-MeV-proton impact. K-Auger electron spectra observed in these measurements are compared to similar spectra from gas targets and to calculations based on Monte Carlo track-structure techniques. The calculations are shown to accurately reproduce the Auger spectral shapes observed with foil targets. These calculations illustrate the significance of inelastic-scattering processes on the spectra of Auger electrons emerging from foil targets. The potential influence of multiply scattered Auger electrons on the interpretation of Auger spectra observed in beam-foil spectroscopy is illustrated.

INTRODUCTION

The study of Auger-electron emission from foil excited heavy-ion beams has become the subject of increasing activity. Measurements of Auger-electron intensities and energies provide detailed information on the degree of excitation and ionization of projectile ions. The determination of Auger-electron intensities emitted by projectiles emerging from foils can be complicated, however, by the presence of Auger lines characteristic of the foil. The subtraction of foil-contributed Auger lines from projectile Auger spectra depends on accurate knowledge of the shape of the respective spectra if reliable intensities are to be obtained. Although Auger-electron emission from foil targets has been the subject of considerable study,[1-8] little quantitative work has been advanced regarding the shape of the degraded portion of the Auger spectrum. In the present work, the shape of the carbon K-Auger spectrum is deduced from proton impact on a carbon foil where only electrons originating from the target are present. The spectral shape measured under relatively low-energy resolution ($\sim 3.5\%$) is compared to carbon K-Auger spectra from a gas target (C_2H_6) and to calculations carried out using a Monte Carlo track-structure code which follows the degradation of electrons produced in the foil. These calculations allow an estimate of the actual shape of the moderated Auger-electron spectra alone and its dependencies on emission angle and foil thickness and thus provide new information on this background process in beam-foil spectroscopy. The Monte Carlo technique is particularly useful in that spectral line shapes can readily be calculated to a relatively high degree of accuracy for arbitrary foil and beam parameters.

INSTRUMENTATION

Electron-energy spectra resulting from 1-MeV-proton bombardment of thin carbon foils were obtained using the electron-energy-analysis system previously described in detail for the study of gas targets.[9,10] For the present work, the differentially pumped gas target was replaced by a foil holder capable of holding six separate foils. The foil holder could be rotated and data were accumulated for foil orientations of 90 and 60° with respect to the proton beam. Foil thicknesses of nominally 3 and 20 $\mu g/cm^2$ were investigated in the experimental part of this work.

The spectra of electrons ejected from the foil were recorded from a few eV to several keV at various angles from 50 to 125° with respect to the 1-MeV-proton beam. A base vacuum of approximately 1×10^{-6} Torr was maintained and the time between inserting the foil into the vacuum system and accumulation of data was minimized to reduce the effects of foil contamination resulting from absorption of pump oils and other vacuum contaminants. No changes in the electron-energy spectra

were observed for times up to eight hours following insertion of the foil into the vacuum system. For longer times, some change was observed in the low-energy portion of the electron emission spectra. All data presented here were obtained within a few hours of foil insertion into the vacuum system and foil contamination is not expected to influence the results. For the analysis of carbon Auger electron spectra, the electron-energy region from 50 to 300 eV is of primary interest.

EXPERIMENTAL RESULTS

Examples of the electron-energy spectra observed experimentally from 1-MeV protons passing through a 3-μg/cm^2 carbon foil are shown in Fig. 1 for electron emission angles of 50 and 125°. The foil angle used for these data was 90° with respect to the proton beam, i.e., normal incidence. The dashed line drawn under the Auger peak in Fig. 1 is representative of a second-order polynomial fit to the electron spectra above and below this peak as it is usually made lacking better information on the actual shapes of the continuum and Auger spectra. Similar spectra were measured at 10° angular intervals from 50 to 110° (with the exception of the angle corresponding to the foil orientation) and at 125° with respect to the beam direction for foil angles of 60 and 90° and for foil thicknesses of nominally 3 and 20 μg/cm^2. Analysis of the portion of the electron spectra in the region of the Auger contribution is shown in more detail for representative experimental conditions in Fig. 2. These three spectra are obtained for a carbon foil thickness of 3 μg/cm^2. Similar spectra for 20 μg/cm^2 indicate no perceptible change in the shape of the Auger spectra. This may be expected since the 3-μg/cm^2 foil is already thick compared to the range of carbon K-Auger electrons (about 1 μg/cm^2) which are generated throughout the foil by the passing protons.

Although, as we shall show later, the choice of a quadratic fit to the continuum at electron energies < 100 eV and > 300 eV does not provide the most accurate estimate of the continuum background, it does provide a consistent means for evaluating the systematics of the major contributions to the observed Auger spectra. Using the quadratic fit to estimate the continuum, as illustrated by the dashed lines in Figs. 1 and 2, we find that the spectral shape of the moderated Auger electrons is nearly independent of emission angle, foil thickness, and foil orientation. This would be expected theoretically from the nature of the emission process and knowledge of transport properties of low-energy electrons in foils. This arbitrary background estimate also serves to illustrate the princi-

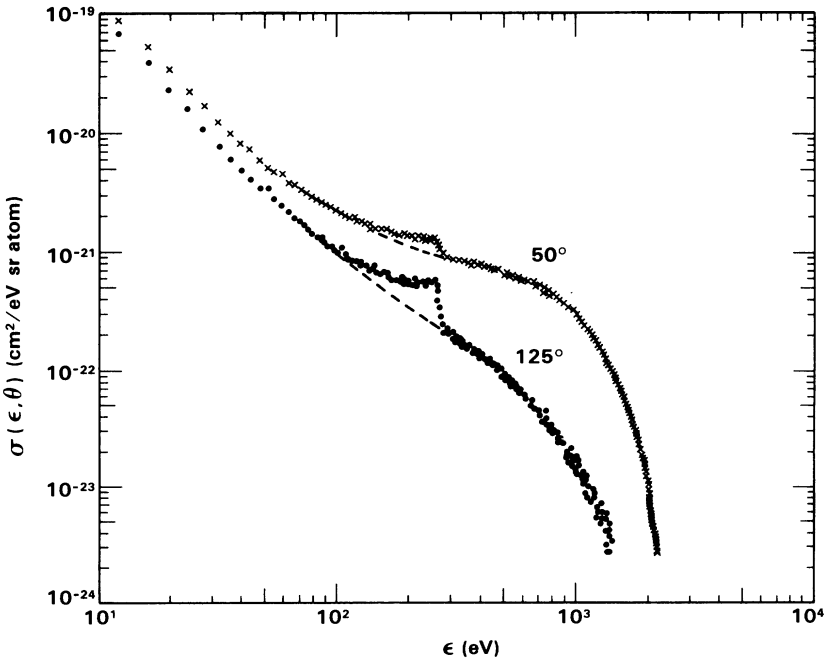

FIG. 1. Experimental electron emission spectra at 50 and 125° for 1-MeV-proton bombardment of a 3-μg/cm^2 carbon foil. The foil is positioned perpendicular to the proton beam.

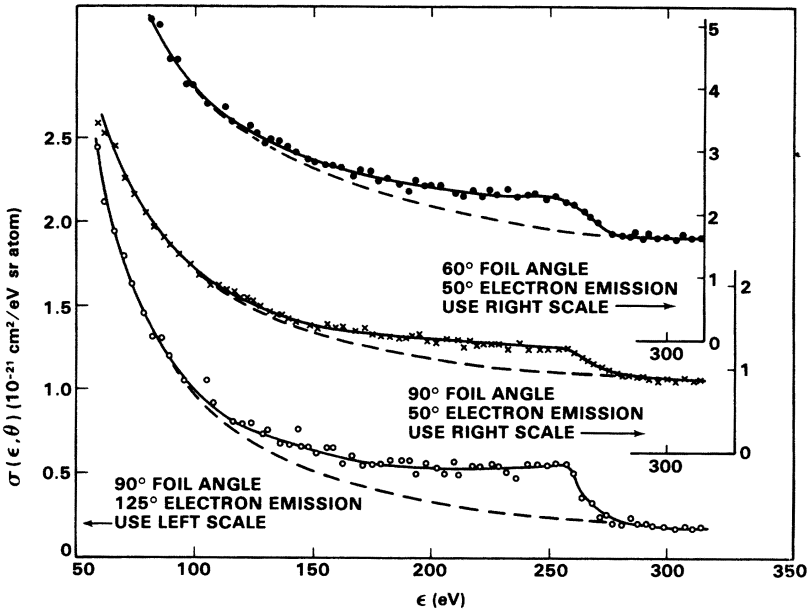

FIG. 2. Experimental electron emission spectra in the energy region of the carbon K-Auger-electron spectrum. The dashed line represents a fit to the continuum above ($\epsilon > 300$ eV) and below ($\epsilon < 100$ eV) the Auger structure.

pal difference between the Auger spectra observed for foil and gas targets. In Fig. 3 we compare Auger spectra obtained from a foil target, after subtracting this background, to that for a carbon K-Auger spectrum measured for the gas target ethane.[11] The ethane spectrum is representative of hydrocarbon targets under low-energy resolution (3.5% FWHM; the foil spectra were obtained with the same energy resolution). Although primary ethane K-Auger spectra are somewhat more Gaussian in shape than spectra from other carbon containing molecules,[11–13] none of the gas target spectra show significant line intensities at electron energies below about 200 eV. This is in marked contrast to the large low-energy tail observed experimentally for moderated Auger electrons from carbon foils. The resolution of the detection system is inadequate and the initial Auger distribution too broad to observe structure due to discrete energy losses by the inelastically scattered Auger electrons.

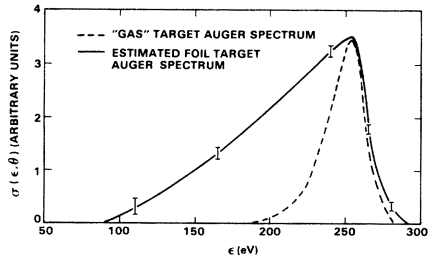

FIG. 3. Auger-electron spectra from foil and gas targets following simple subtraction of the continuum background. The gas target is representative of 1-MeV-proton ionization of ethane presented in Ref. 11. The uncertainties illustrated on the foil spectra encompass the range of values obtained under most of the emission angles, foil orientations, and foil thicknesses investigated; all spectra have been normalized to the same peak height.

PRINCIPLES OF CALCULATION

The doubly differential electron spectrum observed outside a foil target from multiply scattered Auger electrons produced by ion-atom collisions within the foil cannot be resolved easily from the accompanying intense "background" of secondary electrons emitted from outer shells. This makes direct experimental determination of the degraded Auger-electron spectral shape difficult and its characterization as a function of experimental parameters unreliable. One can, however, by means of Monte Carlo techniques, calculate the degraded Auger-electron spectrum directly using knowledge of the ion-atom and electron-atom collision cross sections. In this work we used a Monte Carlo track-structure code to calculate this spectrum to provide information on the shape of the degraded Auger spectrum. The code follows degradation of Auger electrons only and is therefore not complicated by the background of outer-shell-

ionization electrons observed experimentally. The code employed, MOCA-13, was originally developed for radiation biophysical applications and has been designed for water as a model target medium. However, experimental and theoretical experience has shown that for low-Z materials and for electron energies above a few tens of eV, the actual chemical and physical properties of the target medium influence the electron emission cross sections[11,12] and transport characteristics of interest in this context to a minor extent only.[14–16] Those results indicate that the code may be applied also to a carbon foil medium by adequate scaling. A description of the code and comparisons of calculated and experimental results for other physical quantities have been presented elsewhere.[17,18]

For the present investigation, only K-Auger electrons and their secondaries were followed in detail as they were attenuated until they eventually escaped the foil or were stopped within it. Thus "clean," moderated Auger-electron spectra were calculated without the disturbing continuum background from electrons originating from the much more abundant outer-shell-ionization processes. The electrons leaving the foil are scored as to their energy and angle with respect to the proton path. In the bookkeeping procedure an energy bin width of 5 eV was chosen and cosine bin widths between 0.001 and 0.1. Four million Auger-electron histories were followed during the calculation, which corresponds for a 3-μg/cm^2 carbon foil, to about 2.35×10^7 penetrating protons. About 0.17 inner-shell ionizations are produced on the average per proton if a K-shell-ionization cross section of 1.15×10^{-18} cm^2/C-atom for a 1-MeV proton is assumed.[19]

Because we lack precise information on the actual primary Auger-electron spectrum produced by fast protons within the carbon foils, the broad Auger-electron spectrum produced by photoionization of benzene as published by Siegbahn *et al.*[13] was used as the primary spectrum in these calculations. This spectrum was chosen because of the relatively high ratio of carbon to hydrogen and its relatively large molecular weight as compared, e.g., to C_2H_6 or CH_4 where spectra are also available. Since here we are primarily interested in spectra modified by multiple collision processes, and considering the actual experimental energy restriction of 3.5%, the fine details of the initial distribution are not expected to be very critical.

Upon leaving the surface of the foil, the kinetic energy E_1 of an electron is reduced by an amount equal to the surface potential E_A, and the emission angle θ_1 with respect to the foil surface is reduced to θ_2 according to

$$\theta_2=\arctan[-(\sin^2\theta_1-E_A/E_1)^{1/2}/\cos\theta_1]\ . \tag{1}$$

In the present study the surface potential of a carbon foil is about 4.7 eV which is small compared to the electron energies of interest, and the primary spectrum is only an approximate representation. For these reasons and because the above formula applies only to an ideally flat surface, the small corrections in angle (less than 1° at 200 eV and 45° emission angle) have been neglected in our present calculations.

THEORETICAL RESULTS AND DISCUSSION

Results of the Monte Carlo calculations of degraded Auger spectra show a spectral shape of the moderated Auger electrons which differs substantially from the experimental estimates illustrated in Fig. 3. Calculated spectra for a 3-μg/cm^2 carbon foil bombarded by a 1-MeV-proton beam are shown in Fig. 4. The spectra exhibit the following characteristic features: (i) a peak at approximately 255 eV due to primary Auger electrons which exit the foil without significant energy loss: (ii) a series of peaks representing discrete energy loss at energies just below 250 eV: and, here of most importance, (iii) a long tail in the distribution leading to a secondary maximum at very low electron energies. This tail does not decrease to zero at around 100 eV as normally considered, but maintains, even there, an intensity nearly half of that of the primary peak height. The observation of energy-loss peaks in high-resolution electron spectroscopy is well known.[13,20] However, the buildup of low-energy electrons due to degradation within the foil cannot be directly observed. This is because these low-energy electrons produced by ionizing collisions of the Auger electrons are normally masked by production of electrons by other mechanisms; see, for example, the large contribution of low-energy electrons in Fig. 1 and 2 which result primarily from direct ionization of outer-shell electrons of the target atom by the incident proton. Although the degraded Auger spectra shows a factor of nearly 3 increase at 10 eV relative to the peak height at 250 eV, the continuum spectrum increases by nearly two orders of magnitude over the

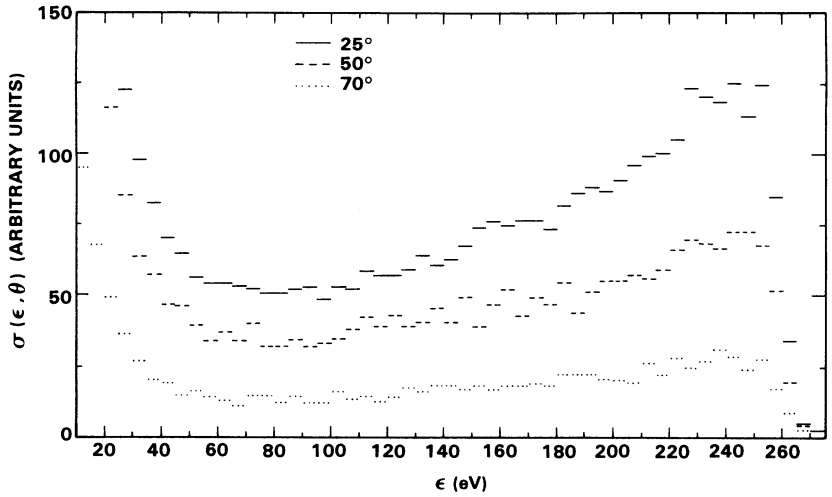

FIG. 4. Calculated electron spectra for electrons exiting a 3-μg/cm^2 carbon foil at 25°, 50°, and 70° resulting from degradation of 260-eV electrons generated randomly along the path of a 1-MeV proton.

same energy range. Note that the relative shapes of the spectra shown in Fig. 4 are also nearly independent of emission angle as expected. There is, however, a relatively strong dependence of the overall intensity on the emission angle.

To provide information on the change in spectral shape with foil thickness we have also calculated the spectra for initial production by proton impact of monoenergetic 260-eV electrons in foils of 0.3 and 1.0-μg/cm^2 thickness. These results are compared to the 3-μg/cm^2 calculations in Fig. 5. The range of a 260-eV electron in carbon is about 1 μg/cm^2 so that one would expect the calculated spectra to be similar for the 1 and 3-μg/cm^2 foils, as observed. For the 0.3-μg/cm^2 foil, the range of 260-eV electrons is greater than the foil thickness and a decrease in the relative number of low-energy electrons is observed. For sufficiently thin foils one would, of course, expect the foil spectra to approach that obtained for single collision gas target measurements where electron scattering is negligible.

The reliability of the Monte Carlo code to provide an accurate Auger line shape can be tested by direct comparisons to our measured spectrum. In Fig. 6 we have plotted the sum of the calculated Auger spectrum, after normalization to the measured peak height at 250 eV, and an estimated continuum electron distribution indicated by the solid line. The estimated continuum assumed in Fig. 6 is approximately 10% smaller for low-energy electron emission than the fitted line shown in Figs. 1 and 2. This reduction reflects the degraded Auger-electron contribution observed in the Monte

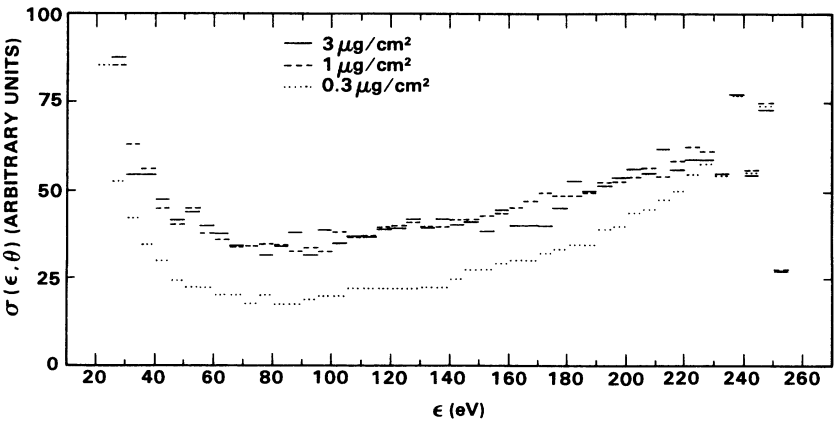

FIG. 5. Calculated electron spectra for electrons exiting a foil at 50° resulting from degradation of 260-eV electrons produced randomly along the path of a proton, in carbon foils of thickness 3.0, 1.0, and 0.3 μg/cm^2.

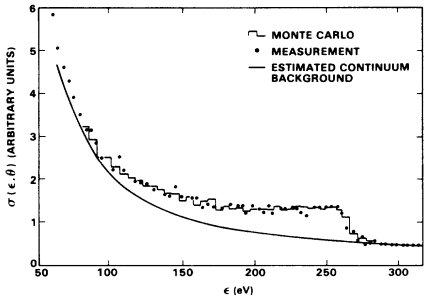

FIG. 6. Comparison of the calculated Auger spectrum exiting a 3-μg/cm^2 carbon foil to the measured spectrum observed at 50° for excitation by 1-MeV protons. The calculated spectrum was normalized to the experimental peak height at 250 eV and added to the continuum background represented by the solid line.

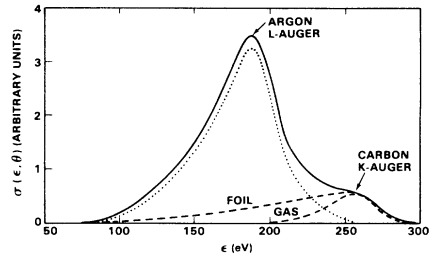

FIG. 7. Auger-electron distribution (Ref. 8) for 400-keV argon passing through a thin carbon foil target. The solid line represents the composite spectrum of argon L-Auger electrons and degraded secondary electrons from the carbon stripper foil. The dotted line results subtraction of the carbon K-Auger contribution. Carbon K-Auger spectra representative of both gas (thin) and foil (thick) targets are illustrated.

Carlo results at low electron energies (see, e.g., the data of Figs. 4 and 5). With this small decrease in the previously assumed continuum contribution the calculated Auger spectral shape is consistent with that observed in the measurement.

As discussed earlier, an accurate knowledge of the moderated Auger-electron spectra originating from foil targets under ion impact can be important in the interpretation of data obtained in beam-foil measurements. To illustrate this point, consider the results shown in Fig. 7 where the composite Auger spectrum is from the work of Baragiola *et al.*[8] In that work, argon L-Auger electrons were observed from argon projectiles emerging from a carbon foil. In order to determine the absolute yield of argon L-Auger electrons, the carbon K-Auger contribution must be subtracted from the composite electron spectrum. In this case the initial carbon Auger spectrum, which is excited by argon projectiles, is expected to be broader and shifted to somewhat lower electron energies than obtained for proton impact.[21–23] The basic shape of the degraded portion of the Auger spectrum is expected to be similar, however, since it depends on the properties of the foil. If a nearly Gaussian shape representative of Auger spectra from a gas target is assumed for the carbon Auger contribution, the carbon K-Auger peak represents approximately 10% of the peak area in agreement with the contribution quoted in Ref. 8. However, when the Auger spectrum representative of a foil target is considered, the carbon K-Auger spectra comprises somewhat more than 20% of the area. In this case, the use of gas phase Auger spectral shapes can lead to a factor of 2 underestimation of the carbon K-Auger contribution to the composite Auger spectra. Although this variation in the background has little effect on the conclusions derived in the work of Baragiola *et al.*, as it is within the quoted experimental uncertainty, this comparsion does illustrate the importance of including the effects of electron degradation in measurement where the intensity of beam and foil Auger spectra are more comparable in intensity.

SUMMARY

The comparison of gas and foil excited Auger-electron-emission spectra show wide differences due to multiple scattering of Auger electrons in the foil. These differences can have important implication in interpretation of foil excited beam Auger transitions where the Auger transitions representative of the foil occur as spectral contaminants. Auger-electron spectra from foil can be accurately calculated using Monte Carlo techniques. This calculational technique is particularly useful in that the variety of experimental parameters can be readily incorporated.

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