X-Ray Production in Ion-Atom Collisions: The Influence of Level Matching*

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Cross sections for L x-ray production in Cu have been measured for collisions between Cu and a wide range of heavy ions and atoms, for collision energies in the range 40 keV to 1.1 MeV. The cross sections show a very strong cyclic dependence on the Z of the collision partner. These data indicate a lack of reciprocity in the roles of target and projectile.

Cross sections have been measured for L x-ray production in copper, for a wide range of collision partners (heavy ions and atoms) in the energy range 40 keV to 1.1 MeV. We have observed a strong cyclic dependence of the cross section on the atomic number of the collision partner, with peak-to-valley ratios as large as 10^3. Cross-section maxima occur for collisions in which the copper L-shell binding energy matches some electronic binding energy in the other particle. The amplitude of the cyclic cross-section variations was found to decrease with increasing collision energy. A similar, though relatively weak, Z dependence for x-ray production cross sections has previously been reported by Specht[1] for the case of "light" and "heavy" fission fragments incident on a wide range of target materials. These data will be discussed in terms of a model presented by Specht[1] and Fano and Lichten[2] in which inner-shell excitations occur at level crossings in the quasimolecule formed during the collision.

The experimental techniques in the present work were like those described in our earlier papers on carbon K x rays,[3,4] except that here copper was used in the role of both target and projectile. Thick metallic targets were used in all cases. The ~940-eV L x rays of copper were detected by a flow-mode proportional counter (energy resolution ~50%) with a beryllium or Mylar window. High-energy data for carbon, oxygen, neon, and argon ions incident on copper were obtained with a Van de Graaff accelerator and for the remainder of the data a 120 kV ion source was used. In the latter case, multiply charged ions were used fairly extensively to extend the energy range. (For example, all the data for copper projectiles were taken using doubly ionized copper. For a given ion kinetic energy the measured x-ray yields were independent of the charge state of the incident ion, to within the experimental errors.) In all cases the collision velocities were small compared with the orbital velocity of a copper L electron. In order to reduce incident-ion buildup and surface-contamination effects all data points were taken from short bombardments (a few microcoulombs of incident beam) on a fresh target spot. All target surfaces were initially cleaned with 600 grit paper and washed in alcohol. The method of calculating an x-ray production cross section from an observed thick-target yield is outlined in Refs. 3 and 4. Stopping cross sections for the incident ions were calculated according to the theory of Lindhard et al.[5] and Firsov[6] for the nuclear and electronic components, respectively. Corrections for x-ray self-absorption in the targets were made using extrapolations of the x-ray absorption coefficients of McMaster et al.[7]

The experimental results are presented in Figs. 1 and 2. Cross sections for copper L x-ray production are plotted (left-hand scale) as a function of the Z of the collision partner, for different, fixed, incident ion energies per atomic mass unit (i.e., fixed ion velocities). Figure 1 shows data for a copper target, for different incident ions, and for several ion velocities. Figure 2 is for copper ions incident on a range of different targets, for a copper ion energy of 160 keV (2.5 keV/amu). Thus in Fig. 1 the copper x rays originated in target atoms, while in Fig. 2 they originated in projectile ions. The dashed lines in Figs. 1 and 2 represent ground-state electronic binding energies (right-hand scale), the horizontal dashed lines are copper L-shell energies, and the dashed curves show the Z dependence of the electronic binding energies for the other particle. In both Figs. 1

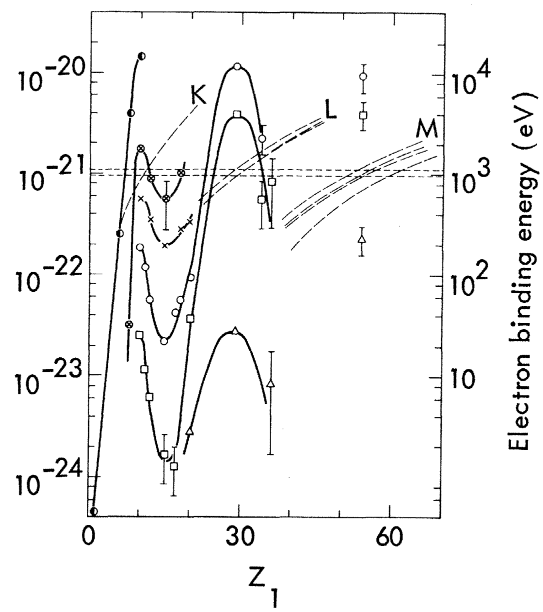

FIG. 1. Cross sections for copper L x-ray production (left-hand scale) in a thick copper target as a function of the atomic number of the incident ion, for different, fixed, ion energies per atomic mass unit (i.e., fixed ion velocities): triangles, 1.0 KeV/amu; squares, 2.0 keV/amu; open circles, 3.0 keV/amu; crosses, 5.0 KeV/amu; crossed circles, 10 KeV/amu; and half-filled circles, 50 KeV/amu. Unless indicated, the experimental uncertainty is about 30%. The dashed lines represent ground-state electron binding energies (right-hand scale): The horizontal dashed lines represent copper L-shell binding energies, and the dashed curves show electron binding energies for the incident ions as a function of their atomic number.

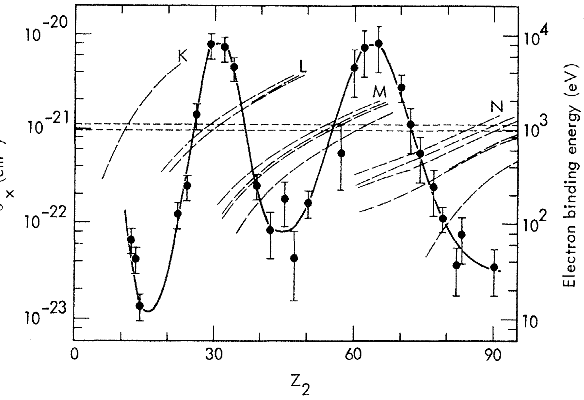

FIG. 2. Cross sections for copper L x-ray production (left-hand scale) in incident copper ions striking solid metal targets, as a function of the atomic number of the target, for a fixed ion energy of 160 keV (2.5 keV/amu). The dashed lines represent ground-state electron binding energies (right-hand scale): The horizontal dashed lines represent copper L-shell binding energies, and the dashed curves show target atom binding energies as a function of target atomic number.

and 2 the x-ray production cross sections show very pronounced peaking for Z values corresponding to a match of the copper L-shell binding energy with some electronic binding energy in the collision partner. The data in Fig. 1 indicate decreasing peak-to-valley ratios with increasing ion velocity. Such a velocity dependence was also noted by Specht[1] in his work with high-energy fission fragments and it explains the smaller peak-to-valley ratios that he observed. Using a value 0.0056[8] for the copper L-shell fluorescence yield, the cross section maxima in Fig. 2 and the maxima for the higher ion velocities in Fig. 1 imply total cross sections for L-shell vacancy production that are essentially equal to the geometrical cross section of the shell. (It should be recognized, however, that conventional fluorescence yield values may not apply to these complex interactions in which a high degree of outer-shell ionization is expected.)

The cyclic structure in the cross-section data of Figs. 1 and 2 is consistent with the interaction model usually applied to ion-atom collisions,[1,2] in which inner-shell vacancies result from level crossings in a dynamic quasimolecule. For the symmetric case (same atomic number for incident ion and target atom) discussed by Fano and Lichten,[2] the electronic levels of the ion and atom involved are changed by the presence of the collision partner, yielding, for adiabatic collisions, a system of molecular orbitals that in the limit of very small internuclear separation become the atomic levels of the "combined atom." As the nuclei approach one another for these slow collisions the exclusion principle dictates the occupancy of these molecular orbitals, some of which may cross with higher, unfilled levels. Electron transitions can occur with high probability at these crossings. This "electron promotion" mechanism, highly pertinent to symmetric collisions, should also be important for asymmetric collisions in which there is a matching of electron energy levels in the two particles. In the cases of asymmetric collisions not involving level matching, corresponding to the minima in Figs. 1 and 2, electron promotion effects would be reduced and small excitation cross sections would be expected.

A lack of reciprocity in the roles of target and projectile is seen from a comparison of Figs. 1 and 2. In the region of considerable data overlap (Z values less than 35) the curve for copper projectiles (Fig. 2) is apparently shifted to the right by one or two units in Z relative to the data for copper as the target. Detailed reciprocity is, of course, not expected since in a solid target the projectile experiences multiple interactions while target atoms do not. Also, outer-shell vacancies are filled rapidly for target atoms residing in a solid. Thus, higher degrees of outer-shell excitation are expected for the projectile. The relative Z shift in the data of Figs. 1 and 2 is, in the context of level matching, consistent with a relative increase in inner-shell binding energies in the projectile; such changes in inner-shell binding energy can result from changes in the outer shells through an alteration of screening.[9,10]

An apparent subshell effect is indicated by a comparison of Figs. 1 and 2 in the Z region 50 to 60. In Fig. 1 the cross sections for xenon on copper ($Z_1 = 54$) appear to be peak values (and correspond to a match of copper L-shell binding energies with xenon $M_{\rm I}$, $M_{\rm II}$, and $M_{\rm III}$ energies), whereas the peak corresponding to L-M matching in Fig. 2 is at $Z_2 \sim 64$ (corresponding to a match with target atom $M_{\rm IV}$ and $M_{\rm V}$ levels). It is not clear at this time whether this represents a difference in the role of target and projectile, or whether, in fact, another peak should be drawn in Fig. 2 in the region $Z_2 = 54$. A related question arises regarding the small cross sections indicated in Fig. 2 in the region $Z_2 \sim 88$ where there are matching ground-state binding energies for the copper L shell and the collision partner $N_{\rm I}$, $N_{\rm II}$, and $N_{\rm III}$ subshells.

It should be noted that in the regions of the peaks in Figs. 1 and 2, excitation of the collision partner produced x rays that were not resolved, by the proportional counter alone, from the L x rays of copper. A study of these collision-partner x rays was required in order to make corrections to the x-ray yield data. In agreement with earlier related observations by Fastrup and Hermann,[11] the copper L x rays overwhelmingly dominated on the high-Z sides of the peaks in Figs. 1 and 2, whereas on the low-Z sides of the peaks lower-energy x rays from the collision partners dominated the spectra. For cases in which the collision-partner x ray was sufficiently lower in energy than the copper L x ray (i.e., well down the low-Z sides of the peaks), beryllium absorbers were used to remove the collision-partner x rays. In the regions very near the peaks a diffraction spectrometer[12] was used to determine a correction factor. On this basis, for example, a ~30% correction was made to the proportional counter data for neon on copper (Fig. 1) because of neon K x rays in the spectrum, and a similar correction was made in Fig. 2 for $Z_2 = 62$ because of samarium M x rays. For points just beyond cross-section peaks, such as for $Z_1 = 12$ in Fig. 1 and $Z_2 = 32$ in Fig. 2, no interfering x rays were observed. For the symmetric case (copper on copper) the proportional-counter data were reduced by a factor of 2, on the assumption that the target and projectile contribute roughly equally. Detailed spectrometer data, showing the x-ray contributions from target and projectile in the regions of the peaks in Figs. 1 and 2, will be published in a forthcoming paper.

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