PRODUCTION OF CARBON CHARACTERISTIC X RAYS BY HEAVY-ION BOMBARDMENT*

R. C. Der, T. M. Kavanagh, J. M. Khan, B. P. Curry, and R. J. Fortner
Lawrence Radiation Laboratory, University of California, Livermore, California 94550

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Cross sections for carbon K x-ray production have been measured for the ions H^+, He^+, C^+, N^+, O^+, Ne^+, Ar^+, Kr^+, and Xe^+ incident on a carbon target, at energies 20 to 80 keV. The cross sections for the heavy ions are several orders of magnitude larger than those predicted by direct scattering theory and are interpreted in terms of the electron-promotion mechanism of molecular orbital theory.

This paper presents results of a measurement of carbon x-ray production by heavy ions. The excitation mechanism depends on an interpenetration of the atomic shells of the projectile and the target atom, in contrast to the direct-scattering mechanism used to describe x-ray production by protons.[1] In the present experiments, the ions H^+, He^+, C^+, N^+, O^+, Ne^+, Ar^+, Kr^+, and Xe^+ were used, in the energy range 20 to 80 keV. The x-ray production (i.e., K-shell excitation) cross sections for the heavy ions are several orders of magnitude larger than those predicted by direct scattering theory.

The experimental techniques were essentially those described in earlier papers on protons.[2] A thick carbon target was used, and carbon K x rays were detected by a gas-flow proportional counter with a 0.25-mil Mylar window. The window functioned as a critical absorber, with 5% transmission for carbon K x rays and negligible transmission for other x rays in the same energy range (e.g., nitrogen K x rays, argon L x rays). The various ion beams were obtained by introducing appropriate gases into the Duoplasmatron ion source.

The x-ray production cross section σ_X for a given projectile energy E was calculated from the thick target yield I by the relation

$$\sigma_X = \frac{dI}{dE}S + \frac{1}{n}\frac{\mu}{\rho}I, \tag{1}$$

where S is the target stopping cross section for the ion in question, n is the number of target atoms per gram, and μ/ρ is the target absorption coefficient for the carbon x rays. In the present work the first term in Eq. (1) dominates. The values used for the stopping cross sections were a combination of calculated nuclear stopping cross sections from Lindhard, Scharff, and Schiøtt[3] and measured electronic stopping cross sections of Ormrod and Duckworth.[4] The K-shell excitation cross section σ_I is related to σ_X by

$$\sigma_X = \omega_K \sigma_I,$$

where ω_K is the K-shell fluorescence yield, taken to be 0.0009.[5]

Excitation cross sections are plotted in Fig. 1 as a function of ion energy per amu. The data shown for carbon are somewhat anomalous in that x rays from both the target and the projectile were detected; no corrections have been made for the contribution from the projectile. The experimental uncertainty is about 30%, primarily due to possible error in the determination of dI/dE from experimental thick-target yield curves.

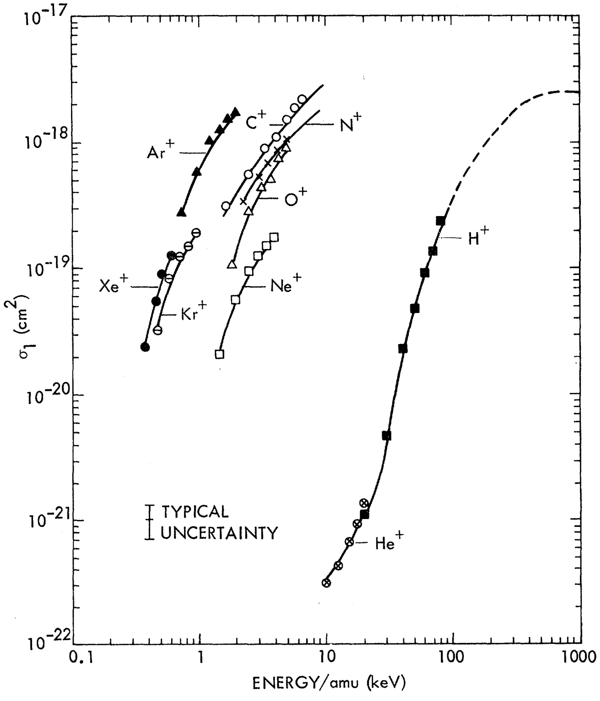

FIG. 1. Carbon K-shell excitation cross section as a function of incident-ion energy per amu. The dashed curve represents higher energy H^+ data from Khan, Potter, and Worley in Ref. 2.

The data for H^+ and He^+ roughly agree with direct-scattering theory; the fact that the He^+ points appear to lie on the same curve as those for H^+ is somewhat surprising in view of the difference of a factor of 2 in Z. The data for heavier ions clearly disagree with direct-scattering theory and the larger cross sections are interpreted in terms of electron promotion in interpenetrating atomic shells, as discussed by Fano and Lichten[6] for the case of Ar^+-Ar collisions.[7] As the projectile approaches the target atom, energy-level splittings occur, and "level crossings" may lead to electron transfers that are manifested as inner-shell vacancies after the separation of the projectile and the target atom. It is believed that this mechanism is not important for H^+ and He^+, since the mismatch in the K levels for the target and the projectile is such that interpenetrating atomic shells produce no vacancies in the K shell of carbon. Thus, the vacancies are produced only by the direct scattering mechanism.

It is interesting to note that at the higher energies the excitation cross sections for Ar^+, C^+, N^+, and O^+ are of the order of the geometrical cross section, where the projectile dimension is taken to be the radius of the shell whose energy most closely matches the carbon K-shell energy. This is consistent with the implication of geometrical cross sections[8] in the Ar^+-Ar case.

This experiment indicates the value of characteristic x rays as an observable in the study of the dynamics of interpenetrating atomic shells. The technique complements related studies based on detection of Auger electrons.[9,10]

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PROPER CHOICE OF FINAL-STATE WAVE FUNCTION FOR DISSOCIATION AND ITS EFFECT ON THE ANGULAR DISTRIBUTION OF DISSOCIATION FRAGMENTS*

Thomas A. Green and James M. Peek
Sandia Laboratory, Albuquerque, New Mexico 87115
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The collisional dissociation of a homopolar diatomic molecule has been heretofore described in terms of a transition to the vibrational continuum of a single Born-Oppenheimer electronic state. This choice of final state, which is shown to be incorrect, yields dissociation-fragment angular distributions which are symmetric about an angle of 90 deg with respect to the beam. The proper final state yields angular distributions which need not possess this symmetry.

In the theory of the collisional dissociation of a rapidly moving diatomic molecule it is customary to use the Born approximation to describe the collision and the Born-Oppenheimer approximation to separate the electronic and nuclear motions in the molecule. The dissociation is then viewed as a transition to the vibrational continuum of one of the electronic states defined by the Born-Oppenheimer separation.[1] We shall show that for homopolar molecules this view of dissociation is incorrect and can (but need not always) lead to wrong angular distributions for the dissociation fragments. The argument will be made for the dissociation of H_2^+ into a proton and a ground-state hydrogen atom. The extension to other cases is conceptually simple, although it may be technically complicated.

Three molecular states enter into the discussion of dissociation to a ground-state hydrogen atom. Initially H_2^+ is in the $1s\sigma_g$ electronic state