Al K x-ray yields with proton clusters*

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Beams of H_2^+ and H_3^+ produce x rays, respectively, with 4% and 8% smaller yields per proton than a H^+ beam of kinetic energies between 90 and 150 keV/amu. These effects are accounted for quantitatively by the enhanced stopping power of Al for ions moving in tight clusters.

INTRODUCTION

Molecular ions have been used frequently to extend accelerator ranges to low energies, under the assumption that the experimental results are independent of whether the particles enter the target as atomic ions or as molecular ions. Recently, large molecular effects have been reported in particle stopping powers[1,2] and in beam-foil spectroscopy.[3,4] When a molecule of velocity v_1 enters a solid, the valence electrons are stripped within a few atomic layers, leaving a cluster of spatially correlated ions to penetrate into the target. Because of Coulomb repulsion, the cluster explodes. The perturbations set up by the ions interfere as long as the inter-ion distances are shorter than the dynamic screening length v_1/ω_0, where ω_0 is the dominant response frequency of the target electrons. These interference effects can have significant consequences for ion-induced processes in the target, and on the final physical states of the emergent projectiles.[5-7] We report precision measurements of relative yields of characteristic Al K-shell x-rays produced by the bombardment of thick aluminum targets with beam of H^+, H_2^+, and H_3^+ of equal v_1 in the range $1.90v_0$–$2.45v_0$, where $v_0=e^2/\hbar$, corresponding to energies, E_1 of 90–150 keV/amu. The yields produced by the di- and triproton clusters are noticeably lower than those produced by H^+ ions, by amounts that are consistent with the strongly enhanced stopping powers of solids for tight ion clusters.[1]

EXPERIMENTAL PROCEDURE

Projectiles from our accelerator were energy selected in a magnetic spectrometer and transported into a target chamber, as shown schematically in Fig. 1. The target was tilted by 45° relative to the incident beam direction and surrounded by a cold trap to prevent carbon buildup. The Al foil was thick compared to the range of the projectiles, and coated at the beam-entrance surface with a platinum film, of thickness 10 ± 1 Å.[8] The energy loss and Coulomb explosion in the Pt layer could be neglected. The Al K x rays were recorded by a Si (Li) detector at 90° from the beam direction. At 135° a surface-barrier detector monitored the particles scattered from the Pt layer, enabling us to determine relative projectile energies with an uncertainty of $\lesssim 0.1\%$. Inasmuch as the x-ray yield, Y, under our conditions depends on E_1 as $Y \propto E_1^n$, where $n \simeq 5$, this limits the relative uncertainty in the x-ray yields to $\lesssim 0.5\%$. The number of incident projectiles was measured through the charge collected by the positively biased target. The double slit reduced the number of particles and electrons that reached the foil through breakup by residual gas molecules and scattering at the slits. Such contributions were analyzed with and without target, in the manner of Fig. 1, and the uncertainty in the charge collection was determined to be less than 1.5%. The yield of protons backscattered by the aluminum foil per proton in H_2^+ and H_3^+ beams was consistently lower by 1%–2% than that backscattered from H^+ beams. We did not pursue this cluster effect further.

RESULTS AND DISCUSSION

The measured x-ray yields are shown in Fig. 2, with experimental uncertainties comparable to the

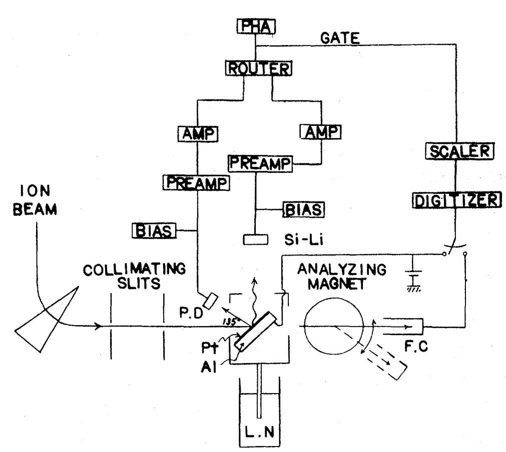

FIG. 1. Schematic diagram of experimental arrangement.

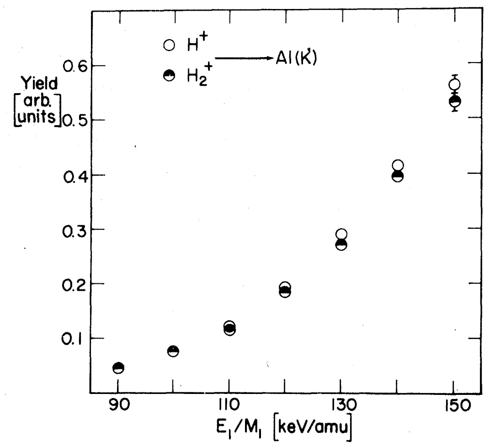

FIG. 2. Aluminum K-shell x-ray yields for projectiles H^+ and H_2^+ in arbitrary units vs incident energy per amu. Statistical errors are comparable to the size of points.

size of the points. The absolute values, not of primary interest here, agree closely with our earlier measurements and with theory.[9] To focus on the cluster effect, Fig. 3 displays the ratios of the x-ray yields for protons in clusters to that for isolated protons.

Collisions leading to Al K-shell ionizations in our velocity range occur at impact parameters ~0.02 Å $= 0.5a_K$(Al) where a_K(Al) is the Al K-shell radius.[9] The projectiles in clusters from molecular ions are always separated by $\gtrsim 1$ Å and, therefore, act as independent particles with regard to K-shell ionization. L-shell ionization requires impact parameters of $\lesssim 0.3$ Å. From geometrical considerations, one estimates the probability of a second proton in a cluster to produce simultaneously an L-shell vacancy to be at most 2%, which would cause a negligible change in the fluorescence yield. Measurements[10] of the nitrogen K-shell Auger-electron and x-ray production cross sections for H^+ and H_2^+ indicate that the fluorescence yields are the same within the experimental uncertainties, although fluorescence yields for H_2^+ ionization appear to be consistently higher than for H^+ ionization. Such a trend would be even smaller in Al with its larger L-shell binding energy. This would imply a slightly higher x-ray production cross section for H_2^+ excitation than for H^+ excitation, and our observation would be a lower limit for the total cluster effect. We take the x-ray production cross sections σ_x to be the same for protons moving as isolated particles or in tight clusters. The measured decrease in x-ray yield should then be caused by the enhanced stopping power of the target for tight clusters.

Let each particle of incident energy E_1 in a homonuclear cluster, consisting of m atoms, lose the energy ϵ during the time τ of initial penetration, $\tau \le \tau_c$, where τ_c is the time during which the clusters explode to interparticle distances larger than the screening length v_1/ω_0.[1,2] Since $\epsilon/E_1 \ll 1$, one has approximately $\epsilon = S_c v_1 \tau_c$, where S_c is the stopping power for particle in the cluster; $S_c = S$ for $\tau > \tau_c$, where S is the stopping power of the isolated particles in a target of atomic density ρ. The thick-target x-ray yield per projectile,

$$Y = \rho \int_0^{E_1} \frac{\sigma_x(E)}{S(E)}\, dE \tag{1}$$

becomes for clusters

$$Y_c = Y - \rho \int_{E_1-\epsilon}^{E_1} \frac{\sigma_x(E)}{S(E)} \frac{S_c(E) - S(E)}{S_c(E)}\, dE\,, \tag{2}$$

which we expand to order ϵ/E_1 by setting $dY/dE_1 = nY(E_1)/E_1$,

$$Y_c(E_1) = Y(E_1)\left[1 - n\frac{\epsilon}{E_1}\frac{S_c(E_1) - S(E_1)}{S_c(E_1)} + O\left(\frac{\epsilon^2}{E_1^2}\right)\right]. \tag{3}$$

We introduce $S_c = Z_c^2 S_p/m$ in terms of the proton stopping power S_p, and the vicinage function ξ^2 defined in terms of the effective cluster charge number Z_c,[1]

$$Z_c^2(\tau \le \tau_c) \simeq \frac{1}{2}\left[\left(\sum_{i=1}^m Z_{1i}\right)^2 + \sum_{i=1}^m Z_{1i}^2\right]$$

as

$$\xi^2 = Z_c^2 \Big/ \sum_{i=1}^m Z_{1i}^2\ , \tag{4}$$

where for protons $m = 1$ and $Z_1 = 1$, for diprotons

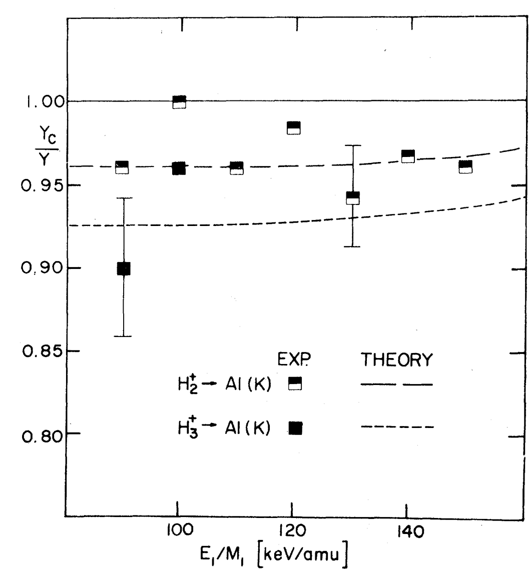

FIG. 3. X-ray yield ratios of H_3^+ and H_2^+ to H^+. Each point represents the average of four measurements. The curves are calculated from Eq. (5).

$m=2$ and $Z_{11}=Z_{12}=1$, for triprotons $m=3$ and $Z_{11}=Z_{12}=Z_{13}=1$. Then

$$Y_c(E_1)=Y(E_1)\left(1-\frac{nv_1\tau_c S_p(E_1)}{E_1}\quad(\xi^2-1)\right). \qquad (5)$$

At high velocities, the target core electrons contribute to the stopping power, which show no cluster effects,[1,2] and the x-ray yield differences shrink. At low velocities, the interference term in Eq. (5) diminishes as the collective component to the energy loss that gives rise to the cluster vicinage effect vanishes.[2] The maximum effect is to be expected in the velocity range $v_1 \sim 2v_0$ where our experiments were performed. The Y_c/Y curves for H_2^+ and H_3^+, calculated from Eq. (5), agree well with experiment, as shown in Fig. 3. Measurements on thick Si targets and thin Al foils also give discernably lower cluster x-ray yields than for protons, in agreement with Eq. (5), but accelerator restrictions prevented us from making quantitative comparisons over an extended energy range.

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