Inner-shell Coulomb excitation in the collisions of few-electron F with H_2 and He†

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The magnitudes, velocity dependences, and Z dependence of projectile K x-ray cross sections measured for 20–56-MeV $F^{7+,8+}$ incident on H_2 and He are well reproduced by direct Coulomb excitation theories, in contrast with previous evidence for multistep excitation processes.

I. INTRODUCTION

Coulomb excitation to bound states in atomic collisions, as opposed to continuum states in ionization, has been extensively investigated[1] almost exclusively for hydrogen, helium, and the outer shells of heavy atoms. The lack of definitive study with the inner shells of heavy atoms presumably lies in the experimental difficulties of distinguishing excitation from ionization in a multielectron system.

We report here a measurement of total cross sections where excitation of inner shell electrons has been isolated with little ambiguity. This was accomplished using few-electron fluorine beams on hydrogen and helium, providing in effect hydrogeniclike and heliumlike F targets. Allowing for screening effects, the magnitudes and energy dependence of the F K cross sections are found to be well characterized by the plane-wave-Born-approximation[2,3] (PWBA) and binary-encounter-approximation[4] (BEA) theories for direct Coulomb excitation to bound states, surprisingly so in view of indications from previous experiments[5,6] of multistep processes in F^{7+}-He collisions. Since Coulomb excitation and ionization are rooted on the same theoretical framework, the present results support the common assumption that ionization dominates in the creation of inner-shell vacancies in the heavy partner of highly asymmetric ion-atom collisions.

We describe the experimental setup in Sec. II and present the results of our measurements in Sec. III. The comparisons of the data and the predictions of direct Coulomb excitation theories are discussed in Sec. IV followed by the assessments of the relative importance of two-step processes in Sec. V and the conclusions drawn from the present study in Sec. VI.

II. EXPERIMENTAL SETUP

Fluorine beams of energies from 20 to 56 MeV were provided by the Stony Brook FN tandem Van de Graaff accelerator. The beam was passed through a thin carbon foil located after the 90° analyzing magnet and the resulting 7+, 8+, 9+ charge states were selected out with a switching magnet. Beam integration was accomplished by monitoring the 90° elastic scattering from a 370-$\mu g/cm^2$ gold foil placed immediately after the interaction region.

The experimental apparatus consisted of a doubly differentially pumped gas cell and a flow proportional counter, which have been described elsewhere.[7] Absorption of F K x rays in the 2-μm Makrofoil entrance window of the flow counter was measured, for both H_2 and He using 36-MeV $F^{7+,8+,9+}$, by recording the yields with and without a second foil between the gas cell and the detector. The existence of single collision conditions was ascertained by checking the linearity of x-ray yield with increase in pressure for the $F^{7+,9+}$ beams, also at 36 MeV. Residual pressure in the target chamber was ~0.1 μm and was found to be due primarily to leakage through the proportional counter window. Operating target pressure for all points was nominally 60 μm as measured with a capacitance manometer. Corrections for yield due to residual gas were significant only in the $F^{9+} + H_2$ cases, for which additional runs were made at the higher pressures of 100 and 200 μm for purposes of verifying the accuracy of the correction.

III. RESULTS

Our measurements of the F K x-ray cross sections are displayed in Fig. 1. These were formed from the peak areas extracted from the spectra by a least-squares-fitting procedure using an analytic function of a gaussian superimposed on a smooth background. The fitting errors are ~10%. Owing to the additional uncertainties in the absorption corrections and the gas cell pressure, the absolute errors are estimated to be ~20%. As-

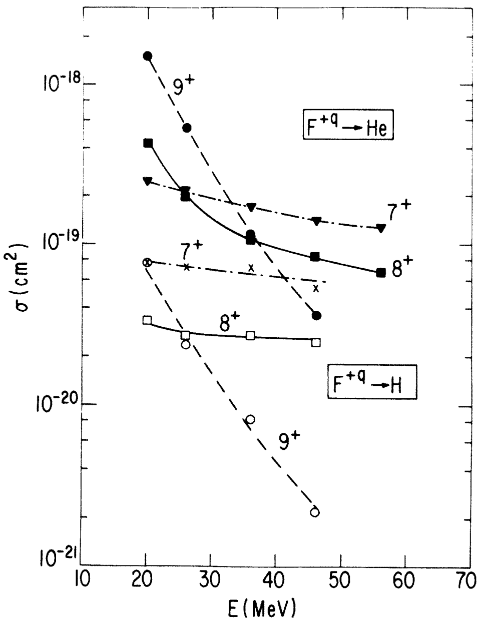

FIG. 1. F K x-ray cross sections for $F^{7+,8+,9+}$ incident on H and He. The curves are drawn to indicate the general trends and have no other significance.

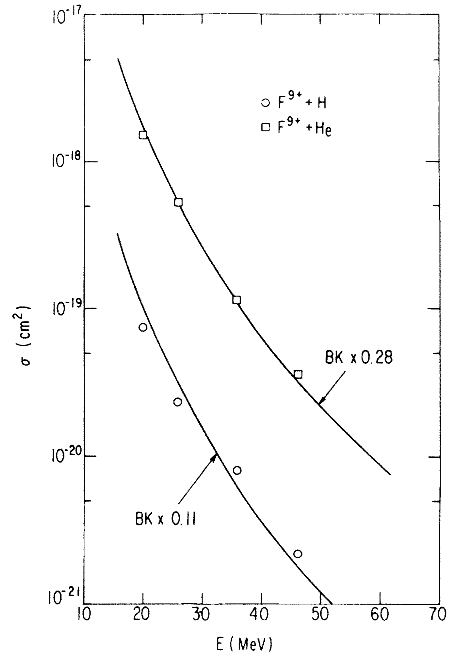

FIG. 2. Comparison of F K cross sections for F^{9+} in H and He with scaled BK theory.

suming here that a diatomic molecule is equivalent to two free H atoms insofar as the F K cross sections are concerned, we present hydrogen cross sections designated hereafter by H, simply the measured H_2 values divided by 2.

The cross sections are seen to vary dramatically with velocity and charge state. These variations reflect the operations of different processes. In the 9+ case, the K x rays can arise only from deexcitation following electron capture (CAP) to any of a number of excited states ($n > 1$). Indeed the theory[8] based on the Brinkman-Kramers (BK) approximation, which has been applied to capture processes over a wide range of atomic shells with good success,[7-9] reproduces well both the F^{9+}+ H and F^{9+}+ He data here when constant scaling factors of 0.11 and 0.28, respectively, are used. Figure 2 demonstrates this agreement.

In contrast, the 7+ data exhibit a relatively flat velocity dependence. In a one-step process, a K x-ray transition cannot result from either capture to $n \geq 2$ levels because the K shell is fully occupied, or ionization in view of the absence of electrons in the higher orbitals. We therefore attribute the 7+ cross sections to direct Coulomb excitation of F K electrons to bound final states (EXC). The probability of two-step processes such as CAP coupled with ionization (ION), although expected to be small, will be discussed in Sec. V.

Both CAP and EXC can contribute in the case of 8+ since the K shell is only occupied by a single electron. This is reflected by the He data where the steep velocity dependence at the low-energy end is characteristic of CAP, while the flat feature at the high-energy end is indicative of the dominance of EXC. In the case of H, all the 8+ points follow the flat velocity dependence for EXC.

IV. COMPARISON WITH THEORY

Considering only one step processes, the discussion in Sec. III leaves little doubt concerning the dominance of EXC in the F K x-ray production for $F^{7+,8+}$+ H and F^{7+}+ He. The EXC contribution to the F^{8+}+ He cross sections can be determined by subtracting the incoherent CAP part, which is taken to be $\frac{1}{4}$ of the corresponding F^{9+} cross sections. The latter procedure is based on an assumption of statistical population, with triplets metastable to K transitions predominant over the singlet states, and on previous experimental measurements.[7] This adjustment is significant only for the lower-energy He points.

To the extent that direct excitation is the main process involved, comparisons of the data with the predictions of direct Coulomb excitation theories are informative and these are shown in Fig. 3. The PWBA calculations are based on the hydrogenic scaling of the proton-hydrogen cross section in the form[2]

$$\sigma(a,b\,|\,Z_1,Z_2,M_2,E) = (Z_1^2/Z_2^4)\,\sigma(a,b\,|\,1,1,1,E/M_1Z_2^2)\ . \quad (1)$$

Here Z_1 and Z_2 are projectile and target nuclear charge, respectively, E is the projectile energy, and $\sigma(a,b\,|\,1,1,1,E/M_1Z_2^2)$ is the cross section for exciting the hydrogen atom from the ground state a to the excited state b by proton bombardment. In the present context, since the roles of projectile and target are switched, $Z_1=1$ (for H) or 2 (for He), Z_2 is the F nuclear charge, and E is the translated energy of the H or He corresponding to F at rest. We neglect for the moment screening due to the bound H and He K electrons. For the proton-hydrogen cross sections, we have used the analytical expressions given by Van den Bos and de Heer.[3] The PWBA curves in Fig. 3 consist of a sum of the $1s\to 2p$ and $1s\to 3p$ cross sections, with higher terms of much smaller magnitude neglected. The BEA results were generated by integrating the expression[4] for the differential cross section per unit energy transfer $d\sigma/d(\Delta E)$ over the ΔE range corresponding to the $1s\to 2p$ transition energy to essentially the K-shell binding energy, and averaging over the velocity distribution[4] of the $1s$ electron.

For the H case, both theories are seen in Fig. 3(a) to reproduce the data well. This agreement is in contrast with the large normalization of the Born (BK) magnitude needed to fit the capture data (see Fig. 2). It also differs from the excitations[1] of more loosely bound shells by H^+, which depart markedly downward from the Born curve over similar values of $\eta^{1/2}$ (=projectile velocity/electron velocity), i.e., ~0.7 to ~1.0. The BEA theory has been reported previously[10] to describe successfully the K-shell ionization for a similar system, $H^+ + Ne$, below velocity matching.

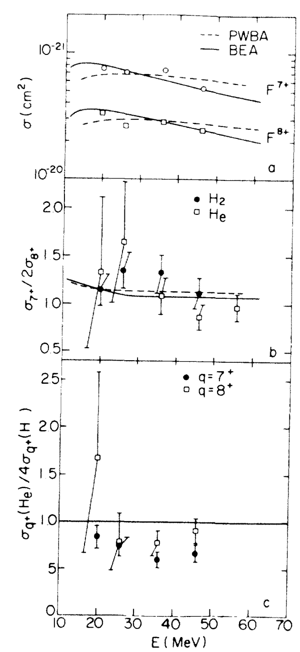

FIG. 3. Comparisons of the measured $F^{7+,8+}$ K x-ray cross sections with the predictions of direct Coulomb excitation theories. Direct comparisons with the H results are shown in (a). Parts (b) and (c) display the cross sections scaled according to the number of F K-shell electrons and the "projectile" Z, respectively.

A different comparison is shown in Fig. 3(b) where the scaling according to the number of electrons in fluorine is examined more closely. The experimental $\sigma_{7+}/2\sigma_{8+}$ ratios are seen to cluster at values slightly above unity. This feature is seen to be accounted for by both theories; in the BEA case, by a decrease[5] in the binding energy of the K electrons for 7+ over that for 8+, while in the PWBA case by a corresponding decrease in the effective nuclear charge due to screening by the other electron ($Z_2=8.7$ was used for F^{7+}). The ratios for He are very similar to those for H.

With respect to the Z dependence of the excitation, a transparent way to exhibit this is to scale the He cross sections by the corresponding H cross sections. These $\sigma_{q+}(He)/4\sigma_{q+}(H)$ ratios are displayed in Fig. 3(c). The relatively large errors for the $\sigma_{8+}(He)$ values at the low energies are the consequence of the correction for CAP in the manner indicated earlier. Both theories predict a uniform value of unity for these ratios. Except for the first highly adjusted 8+ point, the measurements group around a value of ~0.8. Recent calculations[11] of screening effects in K-shell ionization by light projectiles such as $Li^{0,1+,2+,3+}$ suggest that the ~20% depression observed here could very well arise from the difference in screening due to the attached H and He electrons. Calculations of screening effects specific to the present cases would be helpful. In any case, the measurements here afford a unique opportunity to utilize a target atom as a neutral projectile and check such effects at high relative velocities. Further, the complications introduced by charge exchange to the projectile, which may be present[12] in previously reported[13] enhancements in ionization of the Al K shell by bare charge He^{++} over that big H^+, are precluded from the present experiment.

V. TWO-STEP PROCESSES

The excellent agreement between the EXC data and the predictions of direct Coulomb excitation theories strongly suggests that the probability of two-step processes is small. However, two recent experiments involving F K excitation by He within our energy range reported data contradictory to a process of direct excitation which satisfies dipole selection rules. At 35.6 MeV the forbidden spin-flip transition to the $1s2p(^3P_1)$ state is reported[5] to be as prolific as the allowed excitation to the $1s2p(^1P_1)$ state in F^{7+}+ He collisions. The F K x rays from the same collision at 19–33 MeV were found[6] to be polarized to a degree almost identical to that for the K x rays following capture by F^{9+}, deviating from predictions[3] for Coulomb excitation. Both results imply multistep events, such as electron exchange or capture and ionization within a single collision.

More recent experiments[14] investigating the excitation of 30-MeV F^{7+} into the $1s2p(^3P_1)$ state by the heavier gas argon indicate that a large part of that particular triplet cross section arises from excitation of the metastable $1s2s(^3S_1)$ component of the beam. The determination of the 2^2S_1 component in the beams used here has not been made. However, we take the continuity of the data over a large variation in incident energy and the systematics, e.g., comparisons with F^{8+} points, to be consistent with excitation of primarily the ground-state two-electron ion.

With regard to the importance of two-step processes in the excitation of two-electron F, order of magnitude estimates can be make by invoking the independence of simultaneous events within one collision. Thus, for the case of CAP coupled with ION of the F K shell, we can write

$$\sigma(TS)=\sum_{n=2}\int_0^\infty P_n^C(b)\,P_K^I(b)\,2\pi b\,db\ , \qquad (2)$$

where the $P(b)$ are the respective probabilities in impact parameter space b, and n is the principle quantum number. By analogy with the multiple Coulomb ionization formulation,[15] the CAP term in Eq. (2) can be replaced by a constant $P_n^C(0)$ and taken out of the integral, since the integrand is appreciable only for $b\leq A_K$(K shell radius), over which $P_n^C(0)$ is assumed to be relatively constant for $n\geq 2$. Consequently

$$\sigma(TS)=\left(\sum_{n=2}P_n^C(0)\right)\sigma_K^I\ , \qquad (3)$$

and the velocity dependence will be determined essentially by the CAP part since σ_K^I is nearly constant over the present velocity range. For our purpose, we can write $P_n^C(0)=\sigma_n^C/2\pi A_n^2$ where A_n is the Bohr radius for the nth level in F. Using the uniformly scaled σ_n^C values from BK theory and the BEA value[15] for σ_K^I, we obtain the two-step curve for He shown in Fig. 4. The magnitude of $\sigma(TS)$ is at most ~2% of the observed cross section. The same analysis for H yields a ~$\frac{1}{18}$% upper limit.

A similar assessment for electron exchange is precluded by a lack of a specific theory for the

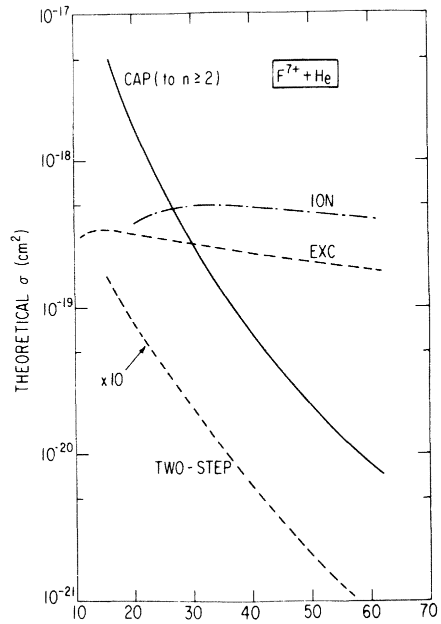

FIG. 4. Representation of the two-step contribution to the He-induced cross sections, derived as described in text.

process. For a two-step mechanism where correlation is unimportant, arguments similar to those above would make it seem unlikely that it would lead to the same features as those for Coulomb excitation, particularly the velocity dependence.

VI. CONCLUSIONS

The measurements of projectile K x rays from few-electron F ions incident on H_2 and He are seen to provide a relatively clearcut opportunity for the observation of excitation of inner shell electrons to bound states. The excitation of one- and two-electron F by H is predicted with accuracy by the simple Coulomb excitation theories. The scaled cross sections $\sigma_{q+}(\mathrm{He})/4\sigma_{q+}(\mathrm{H})$ lie slightly below unity, a feature which probably indicates the importance of screening in the excitation process. The current results do not appear to support previous assertions that multistep processes play significant roles in the excitation of F^{7+} by He. Finally, the agreement between the measurements here and theory lends credence to the common assumption that direct excitation to bound states is negligible compared to the companion process of ionization in the production of inner-shell vacancies in heavy neutral partners involved in highly asymmetric collision, due to blocking of the most probable excitation channels.

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