Electron excitation and capture in F^{8+} plus Ne collisions

Patrick Richard, Philip L. Pepmiller, and K. Kawatsura*
James R. Macdonald Laboratory, Kansas State University, Manhattan, Kansas 66506
(Received 20 November 1981)

K x-ray spectra from the nearly symmetric collision system F^{8+} plus Ne were obtained over the bombarding energy range from 10 to 40 MeV with sufficient spectral resolution to observe separately the K x-ray transitions from states formed by K-shell electron excitation and electron capture to excited states of fluorine. The cross sections for the two processes were obtained by normalization to total K x-ray production cross sections. The K x-ray production cross section for electron capture to excited states falls off by a factor of 40 over the energy range of 10 to 40 MeV, and the K-shell electron excitation cross section increases by a factor of 4 over the energy range 20 to 40 MeV. The K-shell excitation cross section has an energy dependence quite different from that observed for the asymmetric systems.

I. INTRODUCTION

K-shell electron excitation and/or capture to excited states of one-electron projectiles with $Z > 6$ have been investigated for only a few cases. Hopkins *et al.*[1] measured the relative intensity of electron capture to K-shell excitation of F^{8+} and O^{7+} for He, Ne, and Ar gas targets with the use of a high-resolution spectrometer, but did not measure the absolute cross sections. The first measurements of the cross sections for both electron excitation and electron capture were performed by Tawara *et al.*[2,3] for $F^{8+}+$He collisions over a broad energy range. In addition, the total K x-ray-production cross sections by one-electron ions, not distinguishing energetically the K x rays from capture and excitation, have been measured for several projectiles on He.[4–6] In the latter studies, the energy dependence of these cross sections was compared to the energy dependence of the cross sections for capture by bare ions, and showed an enhancement at the high velocities which was attributed to the relative importance of electron excitation in the one-electron projectile at the high velocity.

The only high-resolution study of the cross section for one-electron projectile excitation for nearly symmetric collisions $Z_1 \sim Z_2$ is by Pepmiller and Richard[7] in the study of $F^{q+}+$Ne for $q=2$ to 9, but at only one bombarding energy. Total x-ray-production cross sections for one-electron projectiles have been measured for $F^{8+}+$Ar by Brown *et al.*[8] and Hopkins *et al.*,[9] and for $Cl^{16+}+$Ar by Macdonald *et al.*[10] Of the latter three measurements, only the data of Hopkins *et al.*[9] showed the effects of electron excitation in the total cross section at the high energy.

The present work represents the first direct energy-dependent study of the x-ray-production cross sections for electron capture and excitation of one-electron projectiles in nearly symmetric systems ($Z_1 \sim Z_2$). The measurements were performed using high-resolution x-ray spectroscopy to obtain the relative x-ray-production cross sections and were normalized to the total cross-section measurements of Woods *et al.*[11] Measurements are presented for the one-electron excitation and single-electron capture to excited states for $F^{8+}+$Ne collisions in the bombarding energy range of 10 to 40 MeV.

II. EXPERIMENTAL PROCEDURE

This experiment was performed with the 6-MV tandem accelerator at the James R. Macdonald Laboratory at Kansas State University. The beams were generated in a diode ion-source run on a hydrogen plasma seeded with SF_6. Directly extracted F^- beams were energy selected by a 20° inflection magnet and accelerated to the terminal of the tandem. A gas stripper in the terminal stripped the beam to F^{4+}, F^{5+}, or F^{6+}, depending on the terminal voltage used. The beam was then accelerated to its final energy, focused, and analyzed by a 90° bending magnet and then passed through thin ($\sim 5 \mu g/cm^2$) carbon post-stripper foils. The beam was then analyzed by a switching magnet in which the F^{8+} beam was selected. The beam was focused through two sets of adjustable four-jaw slits upstream from the gas cell and through 3-mm diameter entrance and exit apertures of the gas cell. The first four-jaw slit was used to define the beam size (<3 mm diameter) and the second slit served as a clean-up slit. This geometry minimized the background radiation due to the beam hitting any part of the gas cell and resulted in the best peak-to-background x-ray spectra. A lead brick (~ 7 cm long) served as a radiation shield between the gas cell and the x-ray detector. The final beams transmitted to the Faraday cup ranged in charge intensity from 200 to 20 nA.

The gas cell used in the experiment was contained in a chamber ~ 15 cm in diameter which was differentially pumped by a 6-in diffusion pump. The gas cell had a beam path of ~ 0.5 cm before reaching the x-ray spectrometer slit 0.38 mm wide by 12.5 mm long (parallel to the beam path). The gas was injected into the cell through a needle valve and monitored by a baratron gauge. The pressure dependences of the x-ray yields have been measured earlier,[7] and found to be linear through a pressure of 40 mT. At higher operating pressures a significant fraction of the fluorine ions suffer multiple collisions which affects the yields.

The spectrometer used to measure the x-ray spectra was a 10.2-cm rubidium ammonium phosphate (RAP) Johansson curved-crystal x-ray spectrometer.[12] The gas-cell spectrometer slit served also as the entrance slit of the analyzing crystal. In this geometry a resolution of ~ 3 to 5 eV over the dynamic range was obtained for the x-ray spectra of F. The spectrometer was equipped with a stepping motor for automatic scanning. The logic decisions for dwell time, number of motor steps, and number of x rays counted during each dwell time were performed by CAMAC electronics interfaced to a PDP-11 computer. The photons were detected with a gas flow (P10—10% methane, 90% argon gas) proportional counter operated at +2000 V. The detector pulses were amplified and discriminated in energy by use of a single-channel analyzer (SCA). The logic pulses from the SCA were then delivered to the CAMAC system.

The x-ray spectra for $F^{8+}+Ne$ obtained in this work were corrected for crystal reflectivity, detection efficiency, and lifetime[1] in order to obtain the correct relative x-ray yields R_i. These yields were used to obtain the absolute cross section σ_i of each x-ray transition from the formula $\sigma_i = R_i \sigma_x(8+)$ where $\sigma_x(8+)$ is the total x-ray-production cross section for $F^{8+}+Ne$ collisions. The total cross sections were measured in a separate experiment[13] in which the $F^{q+}+Ne$ reaction was measured for $q=3$ to 9 and from 5- to 40-MeV bombarding energy. It is important to note that all the absolute cross sections are based on the results of Woods *et al.*[11] who reported the F *K*-Auger production cross section to be 2.7×10^{-18} cm^2 for 15-MeV $F^{3+}+Ne$. The x-ray-production cross section is obtained by multiplying the above cross section by the average fluorescence yield of 0.17. This value was obtained from the high-resolution data of Pepmiller and Richard.[7]

III. RESULTS

The fluorine *K* x-ray spectra for $F^{8+}+Ne$ at 20 and 35 MeV are given in Fig. 1 over a photon

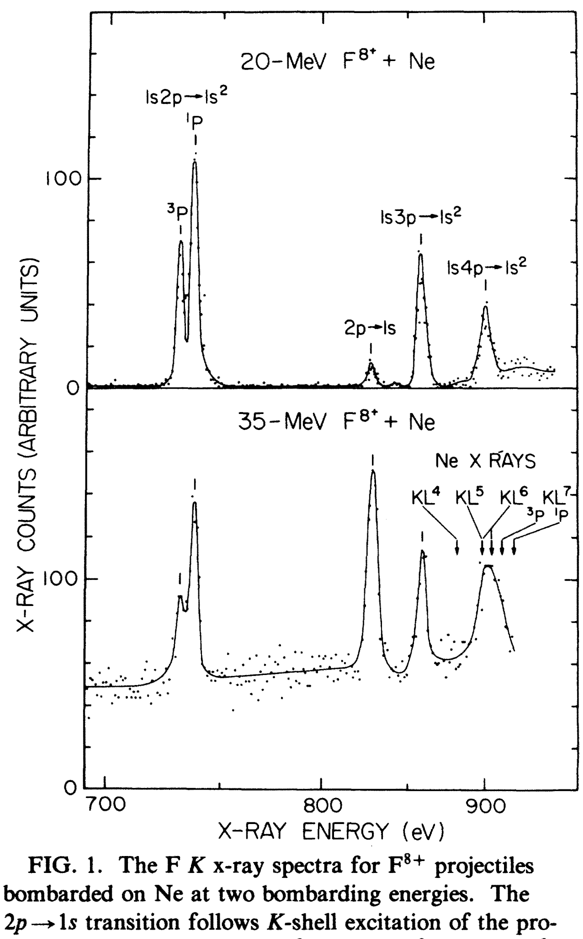

FIG. 1. The F *K* x-ray spectra for F^{8+} projectiles bombarded on Ne at two bombarding energies. The $2p\to1s$ transition follows *K*-shell excitation of the projectile whereas the $1s2p\to1s^2$, $1s3p\to1s^2$, $1s4p\to1s^2$ transitions follow capture to excited states. At 35 MeV the Ne target *K* x rays become prominent and are indicated in the figure.

range of ~680 to 930 eV. Easily resolved are the x rays resulting from electron capture (i.e., the decay of the $1s2p\,^3P$, $1s2p\,^1P$, $1s3p$, and $1s4p$ states) and from electron excitation (i.e., the decay of the hydrogenic $2p$ state). The 20-MeV spectrum is relatively free of background, whereas the 35-MeV spectrum has a significant background yield due to nuclear reactions. The background yield increases so rapidly with projectile energy that above 40 MeV it is nearly impossible to distinguish the projectile K x rays from the background and is thus the limiting energy for thin-gas-target experiments of this type. The background radiation scatters directly into the proportional counter and competes favorably with the K x rays, due to the low efficiency ($\sim 10^{-5}$) for Bragg reflection from the crystal.[1] An additional complication, due to the near symmetry of the projectile and target, is shown in the 35-MeV data where the energies of the K-shell satellite x rays of neon are noted. Owing to this overlap of photon energies the fluorine heliumlike and hydrogenlike transitions could not be reliably measured out to their series limit for the higher incident energies, where the target x-ray production becomes significant. At these energies it was necessary to use the intensity ratios measured at lower energy and for He targets in order to calculate total cross sections for electron capture and electron excitation.

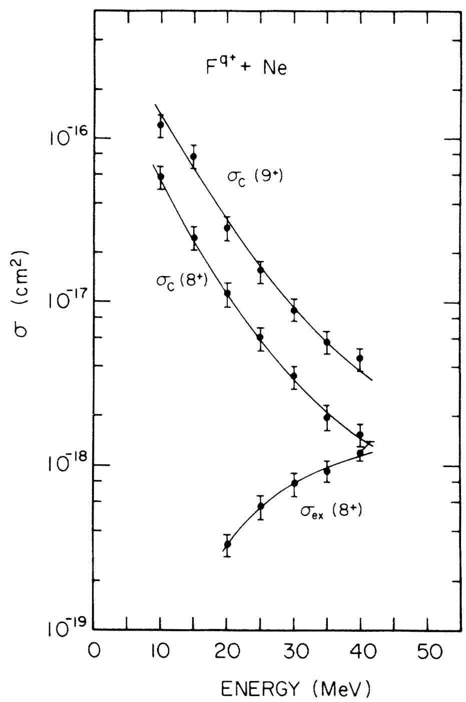

FIG. 2. Total cross sections are given for one-electron capture to excited states by bare (F^{9+}) (Ref. 13), one-electron (F^{8+}) projectiles, and one-electron excitation of one-electron (F^{8+}) projectiles.

A graphical presentation of the measured cross sections is presented in Fig. 2 which gives the total cross-section measurement of Kawatsura *et al.*[13] for F^{9+}+Ne and the present measurements of the cross sections for one-electron excitation and single-electron capture to excited states for F^{8+}+Ne. The cross section for single-electron capture to the F^{8+} decreases by a factor of 40 in going from 10 to 40 MeV, while the cross section for electron excitation approximately quadruples between 20 and 40 MeV. Although the energy at which the cross sections for electron excitation and electron capture are equal was not reached in this experiment, the data can be extrapolated to obtain a value of roughly 45 MeV compared to a measured value of 31 MeV for F^{8+}+He.[2] An experimental difficulty precluded our obtaining an accurate measurement of the cross sections for electron excitation for 10- and 15-MeV projectiles. Charge changing collisions within the beam line result in an estimated 0.3 to 0.5 % of the incident beam arriving on target with a charge of 9+ instead of the desired 8+. The capture of an electron by a 9+ ion is indistinguishable from electron excitation of an 8+ ion. In most cases the impurity fraction adds negligibly to the electron excitation cross section. However, at low energies where the electron capture probability of the 9+ ion is two or more orders of magnitude higher than the 8+ electron excitation cross section, the impurity fraction begins to seriously affect the data. The ratio of counts due to electron capture to a 0.3% 9+ impurity beam versus electron excitation of the 8+ beam is about 1:4 at 20 MeV, and about 4:1 at 10 MeV. Until a pure 8+ beam can be directed on target, or an exact measure of the impurity percentage can be found, no data will be reported for the low-energy electron excitation cross sections. Table I lists the measured x-ray-production cross sections for one-electron excitation, single-electron capture to excited states, total x-ray production of F^{8+}+Ne, and the electron capture cross sections for F^{9+}+Ne of Kawatsura *et al.*[13] all as a function of projectile energy. The relative error in the cross sections is estimated to be 20% and the overall normalization error is estimated to be 50%.

It is informative to present all of the available data for K-shell excitation of one-electron F projec-

TABLE I. K x-ray-production cross sections for F^{8+}+Ne and F^{9+}+Ne in units of 10^{-18} cm^2.

	F^{8+}+Ne			F^{9+}+Ne
E (MeV)	$\sigma_{excitation}$	$\sigma_{capture}$	σ_{total}	$\sigma_{capture}$[a]
10		59.2	59.2	118
15		25.7	25.7	76.2
20	0.33	11.3	11.6	28.2
25	0.56	6.0	6.6	15.2
30	0.78	3.5	4.3	8.9
35	0.92	1.9	2.9	5.7
40	1.2	1.6	2.8	4.5

[a]Taken from K. Kawatsura *et al.*, Ref. 13.

tiles. A graph showing the projectile K-shell electron excitation of F^{8+} incident on four noble gases, which represents all the available data, is given in Fig. 3. Tawara *et al.*[2] obtained high-resolution data for one-electron excitation of F^{8+} on He for the energy range from 12.5 to 35 MeV. The present work, F^{8+} on Ne, covers the energy range from 20 to 40 MeV. Hopkins *et al.*[9] measured the total cross sections for $F^{7+,8+,9+}$ on Ar over an energy range of 20 to 76 MeV, and $F^{7+,8+,9+}$ on Kr over an energy range of 26 to 76 MeV. By subtracting electron capture cross sections, obtainable from the F^{9+} data, from the F^{8+} cross sections, it is possible to obtain that portion of the total F^{8+} cross section due to electron excitation. We have chosen not to plot all of the Tawara *et al.*[2] or Hopkins *et al.*[9] data because it is believed that at lower energies electron capture is so dominant over electron excitation that accurate determination of the electron excitation cross sections is not possible. The uncertainties inherent in the subtraction technique used for extrapolating electron excitation cross sections of F on Ar and Kr are apparent when one considers the error bars shown in Fig. 3. For the near symmetric collisions of this experiment the energy dependence of the electron excitation yield rises more steeply than do the yields for the asymmetric system F^{8+}+He also plotted, over the range of energies studied. In a subsequent comparison of F K-shell electron excitation in F^{6+} and F^{8+} on He collisions[14] it was found that a plane-wave Born-approximation (PWBA) calculation fitted the F^{6+} and the F^{8+} electron excitation cross sections well in both magnitude and shape. The solid curve in Fig. 3 is the PWBA result for He ($Z=2$). A similar calculation has been performed for the system in question now (i.e., Ne, $Z=10$), with less than satisfying results.

Since the data are plotted versus projectile energy and we are considering projectile excitation, the PWBA result changes only by a multiplicative factor. The shape of the data is therefore not reproduced in the calculation, which varies from a factor of 9 too high at 20 MeV to a factor of 2.5 too high at 40 MeV. The magnitude of the calculation is approximately constant over the energy range under study at 3×10^{-18} cm^2.

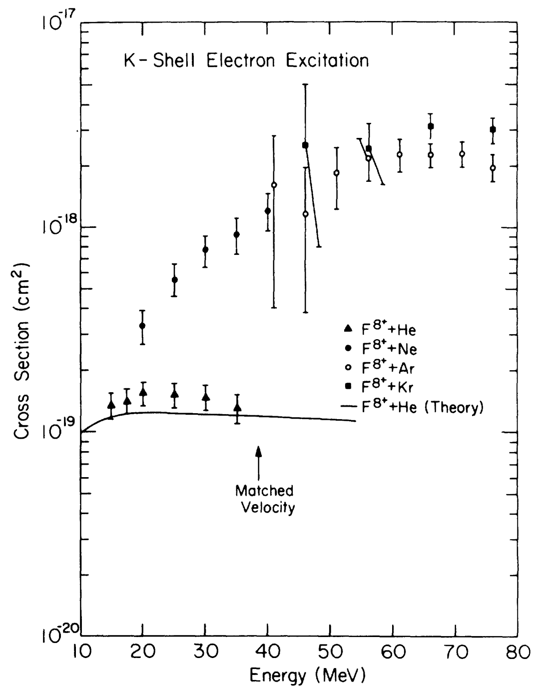

FIG. 3. The cross section for one-electron K-shell excitation of one-electron F^{8+} projectiles for collisions with He (Ref. 2), Ne (present work), Ar (Ref. 4), and Kr (Ref. 4) are presented. Solid curve gives PWBA result for F^{8+}+He.

IV. CONCLUSION

We have measured in high resolution the processes of one-electron excitation and single-electron capture to excited states for the near symmetric system of F^{8+} incident on a Ne target. In this energy-dependent study it has become evident that at low energies (<30 MeV) single-electron capture to excited state is the dominant K x-ray-production mechanism in near symmetric collisions. At higher energies one-electron excitation becomes a comparable K x-ray-production mechanism, due not so much to a rise in the one-electron excitation cross section, as to the 30-fold drop in the probability for single-electron capture to excited states in the energy range of this experiment. The data have been compared with works by other authors who have measured K x-ray-production of F^{8+} after collision with targets lighter and heavier than the Ne target studies here. A target-dependent study of projectile one-electron excitation is analogous to varying the projectiles (He, Ne, Ar, and Kr) incident on an atomic hydrogenic target and studying the target x rays. A plane-wave Born-approximation calculation has been performed for one-electron excitation which reproduces neither the shape nor the magnitude of the experimentally determined cross sections. Questions of screening of the target nucleus in K-shell excitation in heavy ion-atom collisions, and K-shell excitation theories concerning heavy near symmetric systems should be pursued. The main features to be understood, as evidenced in Fig. 3, are (1) the one-electron excitation cross section saturates to a smooth curve as one goes to a large target Z and (2) the peak in the cross section for one-electron excitation of F^{8+} on He is well below the matched velocity of 38.5 MeV, while the peaks for F^{8+} on Ne, Ar, and Kr are all above the matched velocity.

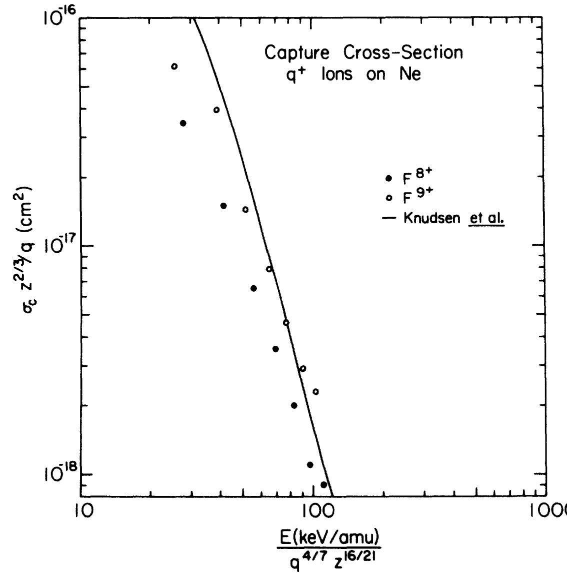

FIG. 4. The cross sections for one-electron capture to excited states for F^{8+} and F^{9+} on Ne are plotted with the scaling coordinates of Knudsen *et al.* (Ref. 15). The solid curve is the total capture cross section predicted by Knudsen *et al.*

The data, for single-electron capture to excited states of F^{9+} on Ne, from Kawatsura *et al.*[13] are again shown in Fig. 4, along with the data for single-electron capture to excited states of F^{8+} on Ne from the current experiment. The data are plotted according to the scaling laws given by Knudsen *et al.*[15] who also give the theoretical model curve shown. Some discrepancy is to be expected between our data and Knudsen's curve since we cannot measure capture into the ground state or long-lived metastable states. However, the shape and the magnitude of the experimental cross sections are reasonably well reproduced.

---

*Permanent address: Japan Atomic Energy Research Institute, Tokai Ibaraki 319-11, Japan.

[1]F. Hopkins, R. L. Kauffman, C. W. Woods, and P. Richard, Phys. Rev. A 9, 2413 (1974).

2 H. Tawara, P. Richard, K. A. Jamison, and T. J. Gray, J. Phys. B 11, L615 (1978).

[3]H. Tawara, P. Richard, K. A. Jamison, T. J. Gray, J. Newcomb, and C. Schmiedekamp, Phys. Rev. A 19, 1960 (1979).

[4]F. Hopkins, A. Little, and N. Cue, Phys. Rev. A 14, 1634 (1976).

[5]J. A. Guffey, Ph.D. dissertation, Kansas State University, 1977 (unpublished).

[6]U. Schiebel, B. L. Doyle, J. R. Macdonald, and L. D. Ellsworth, Phys. Rev. A 16, 1089 (1977); B. L. Doyle, U. Schiebel, J. R. Macdonald, and L. D. Ellsworth, *ibid.* 17, 523 (1978).

[7]P. L. Pepmiller and P. Richard (unpublished).

[8]M. D. Brown, L. D. Ellsworth, J. A. Guffey, T. Chiao, E. W. Pettus, L. M. Winters, and J. R. Macdonald,

Phys. Rev. A 10, 1255 (1974).
[9]F. Hopkins, R. Bren, A. R. Wittemore, N. Cue, V. Dutkiewicz, and R. P. Chaturvedi, Phys. Rev. A 13, 74 (1976).
[10]J. R. Macdonald, M. D. Brown, S. J. Czuchlewski, L. M. Winters, R. Laubert, I. A. Sellin, and J. R. Mowat, Phys. Rev. A 14, 1997 (1976).
[11]C. W. Woods, R. L. Kauffman, K. A. Jamison, N. Stolterfoht, and P. Richard, Phys. Rev. A 13, 1358 (1976).
[12]J. L. Jones, K. W. Paschen, and J. B. Nicholson, Appl. Opt. 2, 955 (1963).
[13]K. Kawatsura, P. Pepmiller, and P. Richard (unpublished).
[14]H. Tawara, M. Terasawa, P. Richard, T. J. Gray, P. Pepmiller, J. Hall, and J. Newcomb, Phys. Rev. A 20, 2340 (1979).
[15]H. Knudsen, H. K. Haugen, and P. Hvelplund, Phys. Rev. A 23, 597 (1981).