Role of excitation in K-shell vacancy production for F^{6+} + He collisions

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Cross sections have been measured for K-shell vacancy production for $F^{6+}(1s^2 2s)$ ions incident on He target atoms in the projectile energy range from 10 to 40 MeV. Collisions leading to $F^{6+}(1s2s2p)$ states are attributed to K-shell excitation. The cross sections for $F^{6+}(1s^2 2s)$ to $F^{6+}(1s2s2p)$ excitation agree with a Born calculation for $1s$-electron excitation. Collisions leading to $F^{7+}(1s2p)$ states are referred to as K-vacancy production to distinguish it from the K-shell excitation process. The energy dependence of the K-vacancy production cross section for the $F^{6+}(1s^2 2s)$ to $F^{7+}(1s2p)$ process does not agree with the calculation for single $1s$-electron ionization. The observed energy dependence is understood in terms of the sum of two two-step processes. One two-step process is $1s$-electron ionization simultaneous with $2s$-$2p$–electron excitation and the other is $2s$-electron ionization simultaneous with $1s$-$2p$–electron excitation. The latter process is dominant. The F^{q+} charge-state dependence at 15 MeV and the F^{8+} energy dependence for electron excitation, as previously reported, are also compared with theory.

I. INTRODUCTION

In a previous paper,[1] the observation of many K x-ray transitions from F ions by high-resolution crystal spectroscopy for 15-MeV F^{q+} ions incident on a He target were reported. The production mechanism (electron capture, ionization or electron excitation) leading to the initial state for each F K x-ray transition was identified and the x-ray production cross section for each was determined. It was shown that the ratios of the excitation process to the ionization process is strongly dependent on the charge state of the F ions and increases more than one order of magnitude in changing from F^{2+} to F^{6+} incident ions. The ratio of the intensity of the $(1s2p)\,^3P$-$(1s^2)\,^1S$ transition to the $(1s2p)\,^1P-(1s^2)\,^1S$ transition of heliumlike F ions is also dependent on the charge state of the incident F ions. The measurements of the K x-ray production cross sections involving F^{8+} and F^{9+} ions incident on He as a function of the incident energy between 10- and 35-MeV were also reported.[2] The F^{9+} + He collisions lead to hydrogenic K x rays due solely to the electron capture process.[3] For F^{8+} + He, the electron capture process is dominant at the lower energies whereas the electron excitation process is dominant at the higher energies.[2,4,5]

The $F^{7+}(1s^2)$ system would seem to be the logical choice for the continuation of these systematic studies of electron excitation and ionization. There is, however, an experimental difficulty in obtaining pure $F^{7+}(1s^2)$ beams. It is well known that a large fraction (~20%) of the long-lived $(1s2s)\,^3S$ state (~275 μsec for F^{7+}) is contained in a two-electron ion beam.[6] In order to study this system it is necessary to first determine the energy dependence of the metastable fraction in the beam. Due to this experimental difficulty, the next simplest system to study is the F^{6+} ion, which has one outer-shell electron in addition to the two K-shell electrons.

In the present work, we have measured the cross sections for K-shell-vacancy production for $F^{6+}(1s^2 2s)$ ions incident on He target atoms as a function of the incident projectile energy. Collisions leading to $F^{6+}(1s2s2p)$ states and $F^{7+}(1s2p)$ states are observed. The former process is attributed to K-shell excitation and the latter process, which is due to one-electron ionization of the ion, is referred to as a K-vacancy production to distinguish it from the K-shell excitation process. These results, together with the previous experimental data on F^{q+} charge state dependence[1] and the F^{8+} energy dependence,[2] are discussed and compared with theory.[7]

II. EXPERIMENTAL RESULTS

The experimental procedures used in this study are almost the same as those described previously,[1,2] with the exception of slightly better energy resolution of the x-ray crystal spectrometer. Further, the Faraday cup used for beam collection was moved 2 m downstream from the spectrometer and the proportional counter used in the spectrometer was shielded by lead to reduce the background count rate. A typical example of the observed K x-ray spectra from F^{6+} ions at 10 MeV is shown in Fig. 1. The second peak (B) corresponds to the $(1s2s2p)\,^2P_- \to (1s^2 2s)\,^2S$ transition[8] (725.0 eV) where the initial state is formed through K-shell electron excitation. The weak first peak (A) corresponds to the $(1s2s2p)\,^4P \to (1s^2 2s)\,^2S$ transition. The excitation to the $(1s2s2p)\,^4P$ state from the ground state $(1s^2 2s)\,^2S$,

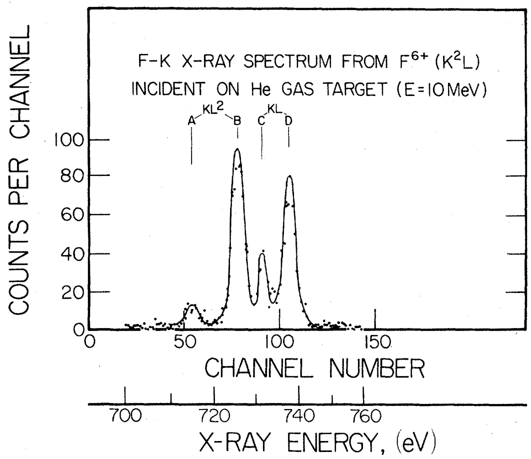

FIG. 1. A typical K x-ray spectrum from F^{6+} ions incident on He atoms. See the text for the origins of each peak.

is prohibited by the pure Coulomb excitation selection rules. The observed ^4P peak may be formed through the electron exchange process between F^{6+} ions and He atoms.[9] The four states of the $1s2p^2$ configuration[8] (e.g., ^2S, ^2P, ^4P, and ^2D) cannot be formed by single-electron excitation. This configuration leads to states very nearly degenerate with peaks A and B. The peak (D) is due to the transition to the ground state $(1s^2)\,^1S$ from the excited $(1s2p)\,^1P$ state which is formed by single K-shell vacancy production of F^{6+} ions accompanied by mixing of the $2s$-$2p$ levels. The mechanisms leading to this type of excitation process will be discussed later. The peak (C) is due to the transition to the ground state $(1s^2)\,^1S$ from the excited $(1s2p)\,^3P$ state which is also formed by single K-shell vacancy production. As the projectile energy is increased the background intensity increases significantly and, therefore, the weak first peak (A) could not be seen in the spectra at the highest bombarding energies.

In Table I and Fig. 2 are shown the measured excitation and vacancy production cross sections of F^{6+} ions incident on He atoms as a function of the projectile energy. To obtain the x-ray production cross sections, the observed x-ray peak intensities were corrected for window transmission and crystal reflectivity by normalizing the intensity at 15 MeV to that measured previously.[1,3] The correction was also made for partial decay-

TABLE I. Cross sections of single K-shell electron excitation (σ_e) and K-vacancy production (σ_v) for F^{6+} ions incident on He are summarized. σ_x is the x-ray production cross section.

E(MeV)	Peak	σ_x(cm^2)	$\sigma_v(^3P+{}^1P)$(cm^2)[a]	$\sigma_e(^2P)$(cm^2)[b]
10	^1P	2.81 ± 0.12 (−20)[c]	4.45 ± 0.38 (−20)	...
	^3P	1.32 ± 0.09 (−20)		...
	^2P	4.08 ± 0.15 (−20)	...	2.13 ± 0.08 (−19)
15	^1P	2.90 ± 0.12 (−20)	8.00 ± 0.38 (−20)	...
	^3P	1.53 ± 0.09 (−20)		
	^2P	4.58[d] (−20)	...	2.39 (−19)
20	^1P	3.18 ± 0.12 (−20)	8.86 ± 0.40 (−20)	...
	^3P	1.73 ± 0.10 (−20)		...
	^2P	5.15 ± 0.20 (−20)	...	2.68 ± 0.18 (−20)
25	^1P	3.33 ± 0.18 (−20)	9.75 ± 0.63 (−20)	...
	^3P	2.07 ± 0.17 (−20)		...
	^2P	5.54 ± 0.24 (−20)	...	2.89 ± 0.13 (−19)
30	^1P	2.81 ± 0.11 (−20)	9.30 ± 0.40 (−20)	...
	^3P	2.34 ± 0.11 (−20)		...
	^2P	5.60 ± 0.20 (−20)	...	2.92 ± 0.10 (−19)
35	^1P	2.63 ± 0.20 (−20)	8.00 ± 0.73 (−20)	...
	^3P	1.80 ± 0.21 (−20)		
	^2P	5.49 ± 0.20 (−20)	...	2.86 ± 0.10 (−19)
40	^1P	1.94 ± 0.30 (−20)	7.55 ± 1.13 (−20)	...
	^3P	2.24 ± 0.42 (−20)		
	^2P	5.57 ± 0.47 (−20)	...	2.90 ± 0.24 (−19)

[a] Fluorescence yield: $\omega(F^{7+})=0.55$. (Theoretical calculation).
[b] Fluorescence yield: $\omega(F^{6+}\cdot 1s2s2p)=0.19$.
[c] 2.81 ± 0.12 (−20) means $(2.81 \pm 0.12)\times 10^{-20}$.
[d] Normalized to the previous value (Ref. 1).

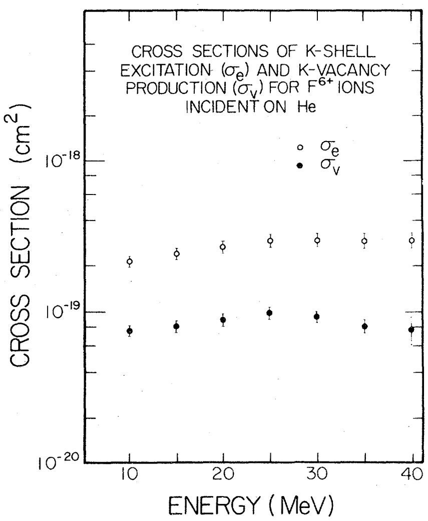

FIG. 2. Measured cross sections of single K-shell electron excitation and single K-vacancy production for F^{6+} ions incident on He.

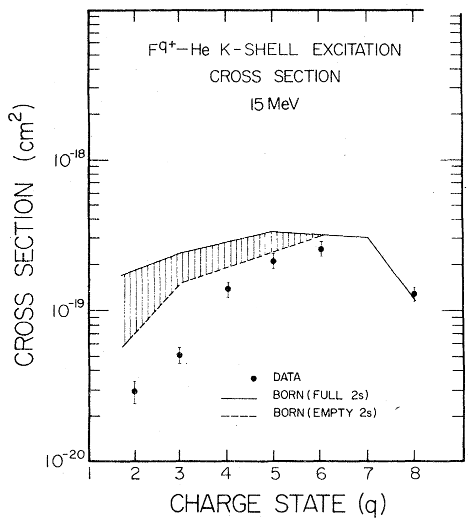

FIG. 4. Comparison between the measured and the calculated incident charge dependence of F^{q+} K-shell electron excitation cross sections in F^{q+}-He collisions.

in-flight of the $(1s2p)\,^3P$ state ($\tau \simeq 0.5$ nsec). The calculated fluorescence yields for each transition[8] were used to convert the x-ray production cross sections to the K-shell vacancy production cross sections.

III. DISCUSSION

The measured cross sections for K-shell excitation in F^{6+} + He collisions change only slightly with incident energy. In Fig. 3, the F^{6+} experimental data are compared with theoretical calculations based on the plane-wave Born approximation.[7] Experimental data for F^{8+} ions on He, which were reported previously,[2] are also shown in the figure, and are compared with theory. The solid curves are for the case of no screening of the He nucleus by its orbital electrons and the dashed curve is for the case of screening ($Z = 1.69$). The theoretical calculation with screening is significantly lower than the data for F^{8+} ions on He. The calculation assuming no screening ($Z = 2$) gives good agreement with the experimental results. It might be reasonable that the screening effect by the orbiting electrons is small since $1s$ electrons of the He atom have a large orbital radius compared to the size of the incident F^{8+} ions. The theoretical calculation for $1s$ electron excitation of F^{6+} ions is also obtained taking $Z = 2$ for He. This calculation also gives good agreement with the experimental data.

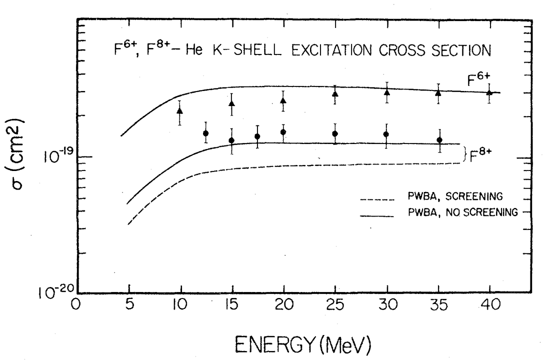

FIG. 3. Comparison between measured and calculated fluorine K-shell electron excitation cross sections in F^{6+}, F^{8+}-He collisions as a function of incident energy.

Using the plane-wave Born approximation mentioned above, the electron excitation cross sections of F^{q+} are calculated for the incident charge states from F^{2+} to F^{8+}, and compared with the measured cross sections reported previously (Fig. 4).[1] Experimentally obtained transition energies between $1s$ and nl levels and a statistical population factor equal to the number of the K-shell electrons times the number of L-shell vacancies, are taken into consideration in the calculations. The excitation calculations for each charge state of F are performed for two situations: one in which the $2s$ level is fully occupied with electrons and another in which it is empty. The cross sections are expected to lie between these two limits. The calculation is found to predict the correct trend and agrees well with the measured cross sections for high-charge states. The calculation, however, overestimates the cross sections for low-charge states. There is a possibility that, for low-charge state ions, a $1s$ electron is excited to a higher level with simultaneous $2p$-electron ionization. This results in the emission of x-ray lines associated with single and double

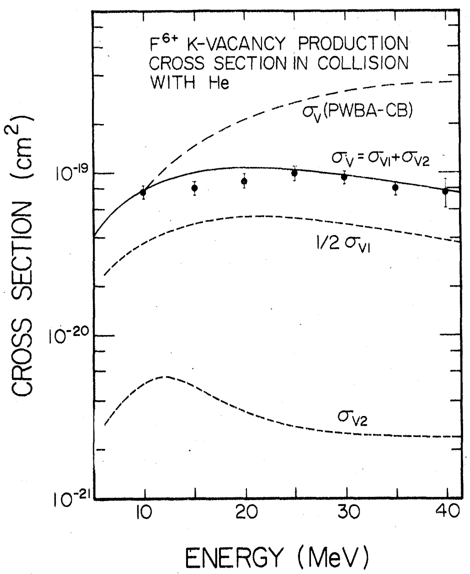

FIG. 5. F^{6+} *K*-vacancy production cross section in F^{6+}-He collisions as a function of the incident energy. The calculated cross sections σ_{v_1} and σ_{v_2} are described in the text.

ionization. The measured cross section for excitation is obtained from the intensity of the lowest-energy x-ray transition, for example the $1s2s^22p^4 \rightarrow 1s2s^22p^3$ transition line for F^{2+}. Therefore, the measured cross section is a lower limit on the excitation process for the low-charge-state ions.

Figure 5 shows the measured F^{6+} *K*-vacancy cross sections for the production of two electron ions (F^{7+}) in the collisions with He. The dashed line represents the theoretical prediction for 1*s*-electron ionization based on the plane-wave Born approximation where He^{2+} ions are assumed to be incident on F^{6+} ions. The calculated cross sections were corrected for Coulomb deflection and increased binding energy effects.[10] Calculations of the polarization effect (distortion)[10] are not included but give slightly larger cross sections and worse agreement with experiment. The observed vacancy production cross sections are nearly constant in the incident energy range from 10 to 40 MeV, whereas the calculated cross sections [plane-wave Born approximation with Coulomb deflection and increased binding corrections (PWBA-CB)] increase by a factor of 5 in the same energy range. The reduced velocity, v_1/v_e, changes from 0.56 to 1.26 (v_1 and v_e are the velocities of the projectile and of the 1*s* electron, respectively) over this energy range. The discrepancy between the PWBA-CB and the observed data becomes significant with the increase of projectile energy. This discrepancy indicates that the vacancy production of F^{6+} in the collision F^{6+} + He is not predicted by a pure 1*s*-electron ionization process.

Collisions leading from $(1s^22s)^2S$ states of F^{6+} to $(1s2p)^1P$ and $(1s2p)^3P$ states of F^{7+} are expected to be described by ionization plus excitation. It is therefore reasonable to assume a model of two-step processes in which both 1*s* and 2*s* electrons of F^{6+} ions are involved simultaneously in either ionization or excitation. Two such processes are possible. In the first process, the 2*s* electron is ionized and one of the 1*s* electrons is excited to the 2*p* state. The total cross section for the process (σ_{v_1}) is described by integrating over impact parameter (*b*) such that

$$\sigma_{v_1} = (2\pi)2 \int p_{2s}^i \, p_{1s}^e (1 - P_{1s}^e) b \, db \;, \qquad (1)$$

where p_{2s}^i and p_{1s}^e are the probabilities of 2*s*-electron ionization and 1*s*-to-2*p*-electron excitation, respectively. In the second process, one of the 1*s* electrons is ionized and the 2*s* electron is excited to the 2*p* state. The total cross section for this process (σ_{v_2}) is described by

$$\sigma_{v_2} = (2\pi)2 \int P_{1s}^i (1 - P_{1s}^i) P_{2s}^e \, b \, db \;. \qquad (2)$$

The total *K*-vacancy production cross section (σ_v) for F^{6+} ions is the sum of σ_{v_1} and σ_{v_2}. We have neglected the interference term between the amplitudes for the two processes. No theoretical calculations are available in the literature for treating these processes coherently. If $P_{1s}^e \ll 1$, $P_{1s}^i \ll 1$, P_{2s}^i changes little at $b \lesssim 2a_{1s}$, where a_{1s} is the radius of F 1*s* electron orbit, then we can deduce the cross sections as follows:

$$\sigma_{v_1} \simeq (2\pi)2 \int P_{2s}^i P_{1s}^e \, b \, db \sim 2P_{2s}^i(0)\sigma_{1s}^e \;, \qquad (3)$$

$$\sigma_{v_2} \simeq (2\pi)2 \int P_{1s}^i P_{2s}^e \, b \, db \;, \qquad (4)$$

where $P_{2s}^i(0)$ is the probability of 2*s* ionization at $b = 0$. P_{2s}^i and P_{1s}^i are estimated from Refs. 11 and 12. For P_{2s}^e, we use the theoretical calculation for 2*s*-2*p* excitation recently developed by McGuire *et al.*[13] The σ_{1s}^e calculation is discussed above. Using the calculations, we obtain both cross sections, σ_{v_1} and σ_{v_2}, and then the total *K*-vacancy production cross section. Figure 5 shows the result of the calculation together with the experimental data.

The cross section σ_{v_1} does not show much change with incident energy, but decreases slightly at low energies. Due to the high probability of 2*s* ionization, σ_{v_1} is large and contributes dominantly to the total *K*-vacancy production cross section. The cross section σ_{v_2} increases with increasing incident energy at low energy, and after attaining

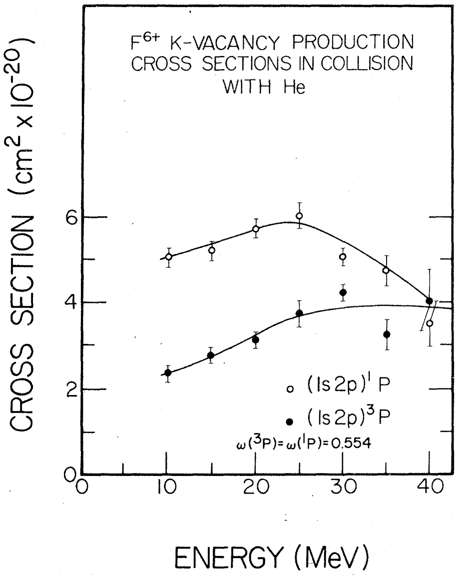

FIG. 6. F K-shell vacancy production cross sections for F^{6+} ions resulting in $(1s2p)\,^1P$ and $(1s2p)\,^3P$ states of F^{7+} in F^{6+} + He collisions. The solid line is drawn to guide the eye.

a maximum value near 15 MeV, decreases with energy. The σ_{v_2} values are less than one tenth of the σ_{v_1}, and therefore the contribution of σ_{v_2} to the total K-vacancy production cross section is minor. As shown in Fig. 5, the present theoretical calculation based on the two-step processes shows fairly good agreement with the measured cross section, not only in the energy dependence, but also in the absolute values. It is concluded that the K-vacancy production process for F^{6+} ions in collision with He is described by the sum of two two-step processes, ionization of $2s$ electron accompanied with $1s$-electron excitation and the ionization of $1s$ electron accompanied with $2s$-electron excitation. The former is the dominant process.

It is noted that the ionization of F^{6+} resulting in the ^3P and ^1P states show different incident energy dependences, as shown in Fig. 6. Ratios of intensities of the $(1s2p)\,^3P-(1s^2)\,^1S$ transition to the $(1s2p)\,^1P-(1s^2)\,^1S$ transition are about 0.5 at lower energies, whereas the ratio approaches 1 at higher energies. This observed ratio of unity at higher energies is expected from the statistical populations for both states if only the $J=1$ states are observed.

IV. CONCLUSIONS

In summary, we have shown that the cross sections for $1s$ to $2p$ excitation of one-electron $F^{8+}(1s)$ and three-electron $F^{6+}(1s^22s)$ can be experimentally measured in collisions with the simple atomic target He by high-resolution x-ray spectroscopy. The observed energy dependence of the cross sections are in excellent agreement with plane-wave Born approximation calculations assuming no screening of the He nucleus by its orbital electrons. This is in contrast to the predictions for outer-shell excitation where distortion affects must be included in the theory to account for the experimental cross sections.[14] For the low-charge states of F the theory is in large disagreement with the measured cross sections. This is probably due to the difficulty in separating the single $1s$-$2p$ process from double electron processes (e.g., double excitation and excitation plus ionization) as discussed in Sec. III.

The K-vacancy production process leading from $F^{6+}(1s^22s)$ to F^{7+} $(1s2p)$ is explained in terms of $1s$-$2p$ excitation simultaneous with $2s$ electron ionization. Our original expectation that the dominant process would be $1s$ ionization proved to be incorrect. In retrospect, this result is not surprising in view of the charge-state dependence of the ratio of $1s$-$2p$ excitation to $1s$ ionization where the ratio is larger than unity for the higher charge states.[1]

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