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Energy-spectroscopic studies of electron-capture processes of low-energy, highly stripped F and Ne ions in collisions with He atoms

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The electron-capture processes of highly stripped ions of F^{q+} ($q=6,7,8$) and Ne^{q+} ($q=7,8,9$) in collisions with He atom were investigated using the energy-gain spectroscopy technique. A single dominant peak is observed in most of the energy-gain spectra except for the Ne^{7+} and Ne^{9+} spectra, in which two peaks are observed corresponding to the one-electron capture process into levels with different principal quantum number *n*.

I. INTRODUCTION

In our recent measurement of total cross sections for one-electron capture processes by highly stripped heavy ions from He atoms at low energies, it was found that the cross sections show significant oscillations when plotted as a function of the ionic charge of the projectile ions.[1,2] This can be explained quantitatively by the classical one-electron model[2] where it is assumed that in such a collision the electron is selectively captured into a particular single level of the ion. To confirm this assumption, we already made a series of measurements of the energy gain of various projectile ions such as C^{q+} ($q=3$–6), N^{q+} ($q=4$–7), and O^{q+} ($q=5$–8) in collisions with He atoms using the translational energy-spectroscopy technique.[3–6] In fact, most of the energy-gain spectra observed show only a single peak which is found to be due to exothermic processes, indicating that the classical one-electron model is valid for these collisions at low energies. However, in some cases such as in the C^{3+}+He collision, four peaks are observed.[5] It was found that they correspond to electron capture into levels with the same principal quantum number *n* but different orbital angular quantum number *l*. Similarly, the energy-gain spectra in N^{4+} and O^{5+} ions become broad indicating the contribution of a number of peaks corresponding to levels with different *l*.

It has also been found that there is good similarity among the energy-gain spectral patterns obtained for different projectile ions with the same ionic charge *q*, irrespective of the ion species: such similarity is considered to result from the similarity among the diabatic potential curves for A^{q+}+He collision systems.[6]

In the present paper, we present new results of our continuing investigation on the electron-capture processes of highly stripped F^{q+} ($q=6,7,8$) and Ne^{q+} ($q=7,8,9$) ions on He atoms. The present experimental principle and technique were already described in detail.[6]

In the following, first, some features in the collision systems investigated are described. All the following experiments have been done at the energy of $q\times1$ keV, where *q* is the ionic charge of the ion. The energy levels of each ion are taken from the book of Bashkin and Stoner.[7]

II. EXPERIMENTAL RESULTS

(i) Ne^{7+}+He [see Fig. 1(a)]: Three peaks are clearly seen. The strongest peak at the energy gain $\Delta E\simeq20$ eV is found to be due to the following one-electron-capture process into the $n=4$ level:

$$Ne^{7+}(1s^22s)+He\rightarrow Ne^{6+}(1s^22s4l)+He^{+}+\Delta E \quad . \quad (1)$$

It is not possible to assign any particular single level because there are a number of closely spaced levels in Ne^{6+} ions.

The second peak at $\Delta E\simeq38$ eV is due to the following one-electron capture into the $n=3$ state:

$$Ne^{7+}(1s^22s)+He\rightarrow Ne^{6+}(1s^22p3l)+He^{+}+\Delta E \quad . \quad (2)$$

It should be noted that this process (2) involves two electrons; that is, one 2*s* electron in the projectile ion is excited into the 2*p* state and the other is captured into the excited 3*l* state of the projectile ion from the target atom. A similar two-electron process has also been observed in the N^{4+}+He collision which results in $N^{3+}(1s^22p^{2}\,{}^1S)$.[5] This observation is the first clear evidence that the electron is captured into levels with different *n*, in contrast to the classical one-electron model which assumes the involvement of only a single level in the one-electron-capture process at low energies.

The very weak peak at $\Delta E\simeq68$ eV is thought to be due to the transfer ionization, as discussed previously,[4] as follows:

$$Ne^{7+}(1s^22s)+He\rightarrow(Ne^{5+})^{**}(1s^22s3lnl')+He^{2+}+\Delta E \rightarrow Ne^{6+}+He^{2+}+e \ , \quad (3)$$

though it is not possible to assure this because no information on the energy levels of such doubly excited states of many-electron systems is available presently. By comparing the integrated areas under peaks with total cross sections previously measured, it is estimated that the cross sections for processes (1), (2), and (3) are 26.1, 4.9, and 1.0×10^{-16} cm^2, respectively.

(ii) Ne^{8+}+He [Fig. 1(b)]: The dominant peak at $\Delta E\simeq31$ eV is found to correspond to the following one-electron capture into the $n=4$ state:

$$Ne^{8+}(1s^2)+He\rightarrow Ne^{7+}(1s^24l)+He^{+}+\Delta E \quad . \quad (4)$$

The weak peak at $\Delta E\simeq63$ eV may be due to the transfer ionization

$$Ne^{8+}(1s^2)+He\rightarrow(Ne^{6+})^{**}(1s^24lnl')+He^{2+}+\Delta E \rightarrow Ne^{7+}+He^{2+}+e \ . \quad (5)$$

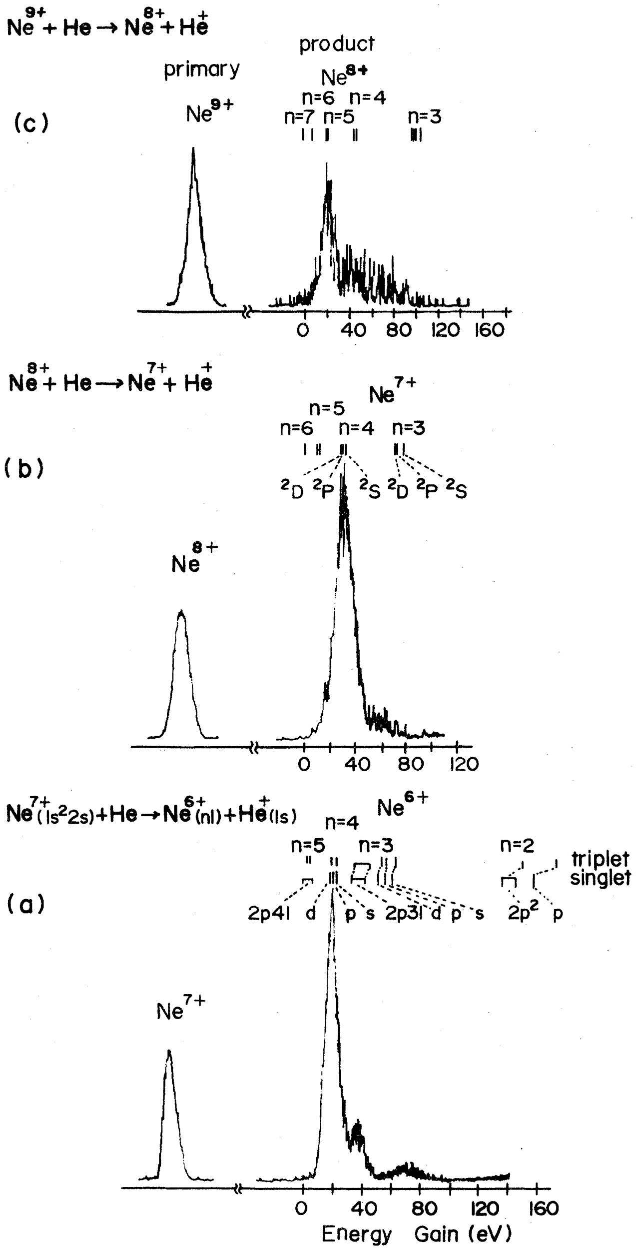

FIG. 1. Energy-gain spectra in (a) Ne^{7+} +He, (b) Ne^{8+} +He, and (c) Ne^{9+} +He collisions.

The intensity for process (5) is roughly 10% of that for process (4).

(iii) Ne^{9+} +He [Fig. 1(c)]: At least two peaks are seen. The stronger peak at $\Delta E \simeq 20$ eV is due to the following one-electron capture into the $n=5$ state of Ne^{8+} ions:

$$Ne^{9+}(1s) + He \rightarrow Ne^{8+}(1s5l) + He^{+} + \Delta E \ . \quad (6)$$

The second peak at $\Delta E \simeq 44$ eV is due to the one-electron-capture process into the $n=4$ state:

$$Ne^{9+}(1s) + He \rightarrow Ne^{8+}(1s4l) + He^{+} + \Delta E \ . \quad (7)$$

The partial cross sections for processes (6) and (7) are roughly 14.5 and 5.5×10^{-16} cm^2, respectively. The very weak peak at $\Delta E \simeq 70$ eV may be due to the transfer ionization as discussed previously.[4]

(iv) F^{6+} +He [Fig. 2(a)]: The observed peak at $\Delta E \simeq 29$ eV is thought to correspond to the following simple one-electron capture:

$$F^{6+}(1s^22s) + He \rightarrow F^{5+}(1s^22s3l) + He^{+} + \Delta E \ . \quad (8)$$

It should be noted that this peak is broader because of the contribution of the levels with different l, with the highest intensity for the $1s^22s3d\,^1D$ level. The weak shoulder at $\Delta E \simeq 18$ eV is thought to be due to the following two-electron process, similar to process (2) in Ne^{7+} +He collisions:

$$F^{6+}(1s^22s) + He \rightarrow F^{5+}(1s^22p3l) + He^{+} + \Delta E \ . \quad (9)$$

(v) F^{7+} +He [Fig. 2(b)]: The stronger peak at $\Delta E \simeq 18$

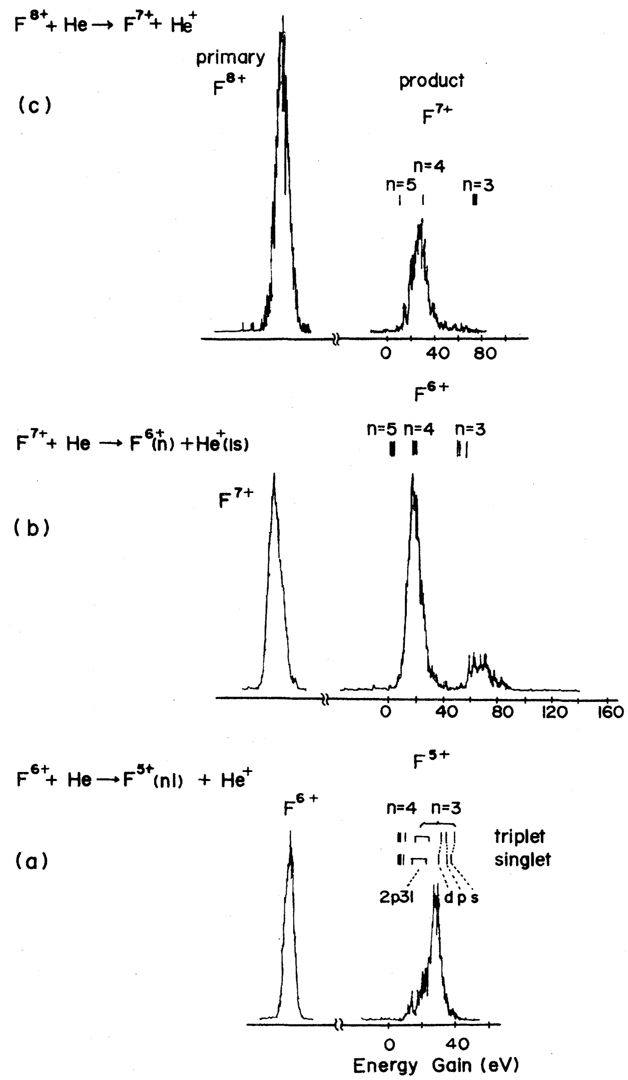

FIG. 2. Energy-gain spectra in (a) F^{6+} +He, (b) F^{7+} +He, and (c) F^{8+} +He collisions.

eV is due to the following process:

$$F^{7+}(1s^2) + He \rightarrow F^{6+}(1s^2 4l) + He^{+} + \Delta E \ . \qquad (10)$$

The weaker peak at $\Delta E \simeq 66$ eV is probably due to the transfer ionization

$$F^{7+}(1s^2) + He \rightarrow (F^{5+})^{**}(1s^2 3l 3l') + He^{2+} + \Delta E$$
$$\rightarrow F^{6+} + He^{2+} + e \ . \qquad (11)$$

By comparing spectra in Figs. 1(a) and 2(b) with previous spectra for N^{7+} and O^{7+} ions,[6] the observed spectra are found to be very similar for all the ions with $q = 7$ except for Ne^{7+} where two different n levels contribute. This similarity of the spectra among different ions with the same ionic charge has been already discussed in detail.[6] However, it should be noted that the transfer-ionization process is much stronger for F^{7+} ions and its intensity amounts to about 20% of that for the main one-electron-capture process (10).

(vi) F^{8+} + He [Fig. 2(c)]: Only a single peak at $\Delta E \simeq 28$ eV is observed which corresponds to the following one-electron capture into the $n = 4$ state of the F^{7+} ion:

$$F^{8+}(1s) + He \rightarrow F^{7+}(1s4l) + He^{+} + \Delta E \ . \qquad (12)$$

As discussed above [see (v)], the very good similarity in the energy-gain spectra is observed in all ions with the ionic charge of $q = 8$ and is understood to be due to the similar energy-level diagrams among them.

III. DISCUSSION

Comparing the observed energy-gain spectra with the energy levels tabulated by Bashkin and Stoner,[7] the principal quantum number n of the electron-capturing levels can be deduced for collision processes and are summarized in Table I which includes our previous data. Data for Ne^{10+} + He collisions are taken from the work of Mann *et al.*,[8] where their collision energy was lower than ours. As can be seen in Table I, the electron-capturing levels are the same for projectile ions with the same ionic charge, irrespective of the ion species. From the observed energy gain ΔE, the curve crossing radius R_c for the one-electron-capture process in the quasimolecule can be determined as shown in Table II through $R_c = 14.4(q-1)/\Delta E$ (q: the ionic charge of projectile ion; ΔE: eV; R_C: Å).[8]

TABLE I. Principal quantum numbers n of the electron-capturing levels in A^{q+} + He collisions.

q	10	9	8	7	6	5	4	3
Ne	5[a]	5(4)[b]	4	4(3)[b]				
F			4	4	3			
O			4	4	3	3		
N				4	3	3	2	
C					3	3	2	2

[a]Data of Mann *et al.* (Ref. 8).
[b]The number in the parentheses is the principal quantum number n corresponding to the weak peak in the energy-gain spectrum.

TABLE II. Crossing radius R_c for the one-electron-capture process in A^{q+} + He collisions (Å).

q	10	9	8	7	6	5	4	3
Ne	4.6[a]	5.7	3.3	4.3				
F			3.6	4.8	2.5			
O			3.4	4.8	2.4	3.1		
N				5.1	2.4	3.6	1.8	
C					2.5	4.2	1.4	2.6

[a]Data of Mann *et al.* (Ref. 8).

In Fig. 3 are shown total one-electron-capture cross sections for various ions investigated in our previous experiment as a function of the crossing radius R_c. For the split distribution of the capturing levels the cross sections are divided according to the observed peak intensity in the energy-gain spectra. In the figure, only data for stronger peaks are shown. The solid line is drawn through data points just to guide the eye, whereas the dotted and dashed curves represent the classical cross sections, that is, πR_c^2 and $\frac{1}{2}\pi R_c^2$, respectively. Classically, it is assumed that the electron capture effectively takes place at the outermost crossing distance R_c inside a critical distance R_x where the attractive force of the projectile ion exceeds the binding force for the electron ion target atom.[6]

From Fig. 3, it is seen that the observed cross sections do not follow the classical cross section πR_c^2 rule. It should also be noted that they do not exceed πR_c^2 for all the range of R_c but are smaller than $\frac{1}{2}\pi R_c^2$ for $R_c < 2.5$ Å and decrease for $R_c > 4$ Å. The existence of a maximum in the cross sections at a particular crossing radius has been report-

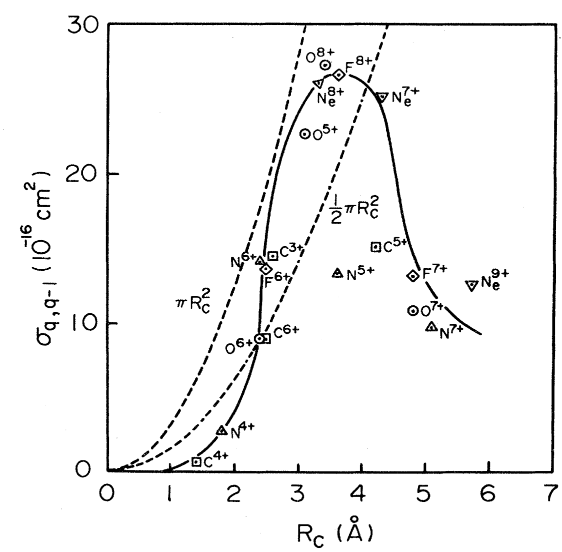

FIG. 3. Total one-electron-capture cross sections vs the crossing radius R_c in A^{q+} + He collisions at around 0.5 keV/amu. Experimental data for C^{q+}, N^{q+}, and O^{q+} are taken from Refs. 5 and 6. The dotted and dashed lines correspond to the classical cross sections. The solid line is drawn through experimental data to guide the eye.

ed by some investigators for various collision systems at different energy ranges[9] and is often called the "reaction window." This window shape seems to be similar for the various cases reported and it tends to be believed to be "universal" for all the collision systems. It is, however, necessary to look at and analyze more carefully the observed data before coming to such a conclusion.

Only in the single crossing system can we theoretically analyze the data relatively easily. In such a single crossing, a Landau-Zener model calculation predicts that the dependence of the cross sections for the charge transfer on the crossing radius R_c is indeed similar in shape to the observed curve (solid line) shown in Fig. 3.[10] It is noted, however, that the R_c dependence of the cross section is strongly dependent on the shape of diabatic potential curves at R_c as well as the collision velocity and, then, could not be universal. Furthermore, even though the observed energy-gain spectrum consists of a single peak, this does not always guarantee a single crossing in the diabatic energy diagram. In fact, we have no accurate idea of how many crossings do contribute to the observed "apparent" single peak in the energy-gain spectrum because of the limited energy resolution used in the experiments. For example, the sublevels having the same n but different l should result in many crossings closely located in the diabatic energy diagram.

On the other hand, if a number of crossings exist at larger crossing radii, many of them may contribute to the total charge-transfer process. Therefore the total cross section could increase with the number of crossings and finally reach the maximum cross section πR_c^2. If there are only a limited number of crossings available in the collision system under investigation, the cross section may not reach the maximum value, as in the present case.

Systematic studies of the l distribution of the electron-capturing levels of higher charge state ions would make it possible to discuss the R_c dependence of the cross section for electron capture in more detail.

As we have shown in Figs. 1 and 2, we observed weak peaks in the energy-gain spectra which we attribute to transfer ionization involving highly stripped ions. Unfortunately, at present there is no accurate data on the energy levels of such doubly excited states of heavy ions.

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