Electron transfer and decay processes of highly charged iodine ions

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Abstract

In the present experimental work we have investigated multi-electron transfer processes in I^{q+} (q=10, 15, 20 and 25) + Ne, Ar, Kr and Xe collisions at 1.5q keV energy. The branching ratios between Auger and radiative decay channels have been measured in decay processes of multiply excited states formed by multi-electron transfer collisions. It has been shown that, in all the multi-electron transfer processes investigated, the Auger decays are far dominant over the radiative decay processes and the branching ratios are clearly characterized by the average principal quantum number $<n>$ of the initial excited states of projectile ions. We could express the branching ratios in high Rydberg states formed in multi-electron transfer processes by using the decay probability of one Auger electron emission.

Keywords: highly charged ion, charge transfer, Auger decay

1. Introduction

To date, multiple electron capture processes in collisions of highly charged ions (HCIs) A^{q+} with atoms B have been widely studied [1]. The electron capture cross sections in HCIs-atom collisions have been understood reasonably well through the classical over-barrier model [2, 3, 4, 5], also the energy deposition model has been used successfully to apply the observed Auger decay processes and multiple ionization processes [6, 7, 8]. Recent activities on those studies are reviewed by Cederquist [9]. Such collisions generally produce multiply excited states

$A^{(q-j)+**\cdots}(n,n',\cdots)$, which in turn are stabilized through emissions of electron(s) and photon(s):

$$A^{q+} + B \to A^{(q-j)+**\cdots}(n,n',\cdots) + B^{j+}$$
$$\to A^{(q-i)+} + B^{j+} + (j-i)e^- + h\nu + h\nu' + \cdots$$

where q represents the charge of the incident projectile ion, j the number of the electrons initially transferred into the ion from target atom during the collision, and i the final charge change of the incident ion after stabilization and $(n,n',\cdots)$ shows the principal quantum numbers of the electron transferred states. Since various combinations of j and i are possible, multiple electron capture processes are so complicated that systematic investigations are needed for the detailed understanding.

In the present study, the previous work has been extended to still higher q to investigate the stabilization processes of higher excited states. In general, the electron transferred levels become higher as the charge of the incident ion increases. We discuss the branching ratios of decay processes as a function of the average principal quantum number "$\langle n \rangle$" of the electron transferred levels.

2. Branching ratios of decay processes

We consider the following multiple electron capture processes in highly charged iodine ion (q=10, 15, 20 and 25) – rare gas atom (Ne, Ar, Kr and Xe) collisions:

$$I^{q+} + B \to I^{(q-i)+} + B^{j+} + (j-i)e^- + \sum h\nu + Q$$

Q is the translational energy gain in the collision, and $\sum$ represents the cascade photon emissions. It is convenient to discuss the electron capture processes by dividing into the following two steps.

I) j-electron transfer process:

$$I^{q+} + B \to I^{(q-j)+**\cdots}(n,n',\cdots) + B^{j+} + Q$$

where $n,n',\cdots$ are the principal quantum numbers of the electronic states produced in this process.

II) Decay process of the excited product ion:

$$I^{(q-j)+**\cdots}(n,n',\cdots) \to I^{(q-i)+} + (j-i)e^- + \sum h\nu.$$

In this paper, we discuss the branching ratios of the above decay processes II) in multiply excited product ions. We have determined the branching ratios in the decay of multiply-excited ions from the coincidence measurement of the scattered and recoil ions. The present experimental apparatus and method were the same as those used in the previous work [10, 11]. The branching ratios $P(j,j-i)$ in the decay of multiply-excited ions by emission of $(j-i)$ electrons after j-electron transfer is defined by:

$$P(j, j-i) = \frac{\sigma^j_{q,q-i}}{\sum_i \sigma^j_{q,q-i}} = \frac{\sigma^j_{q,q-i}}{\sigma^j_q}$$

where $\sigma^j_{q,q-i}$ is i-electron capture and j-electron removal cross section, and σ^j_q is j-electron removal cross section.

We also assume that the Auger decay rates of multiply-excited states with high n-values do not depend strongly on the ion charge, but the number of Auger processes depends on the number of the decay channels from the excited states. Since the number of decay channels is related to the degree of the n-value, the probability of the decay process with j-electrons transferred can be expressed by using the following average value $\langle n \rangle$ of all j electrons: $\langle n \rangle = (n_1+n_2+\ldots+n_j)/j$. Here n_j represents the principal quantum number of the j-th electron transferred which can be estimated from the extended classical-over-barrier-model (ECBM) [12].

Figure 1, 2 and 3 show one of the possible arrangements for the relationship between the branching ratios and the average principal quantum number $\langle n \rangle$. Here, we plot the measured branching ratios as a function of $-1/\langle n \rangle^2$, where $\langle n \rangle$ is the value calculated with the ECBM for each j-electron transfer process. Here we also show the calculated threshold values n_{thre} of the energetically allowed Auger decay processes for the respective branching ratio $P(j,j-i)$. The solid and dotted lines are drawn to guide the eyes, they show the general dependence of the branching ratios on the $\langle n \rangle$-values. In drawing these lines, we take the following simple principles into account: 1) the $P(j,j-i)$ branching ratio is zero when the average transfer levels $\langle n \rangle$ are lower than the threshold levels n_{thre} and 2) the sum of the branching ratios equals to 1.0.

A) Doubly-excited states

In the doubly-excited states (figure 1), we can place the branching ratio of the radiative decay to be 1.0 when the average transfer levels $\langle n \rangle$ are lower than $n_{thre} \cong 5.7$ which corresponds to the threshold levels for the $P(2,1)$ processes. On the other hand, as

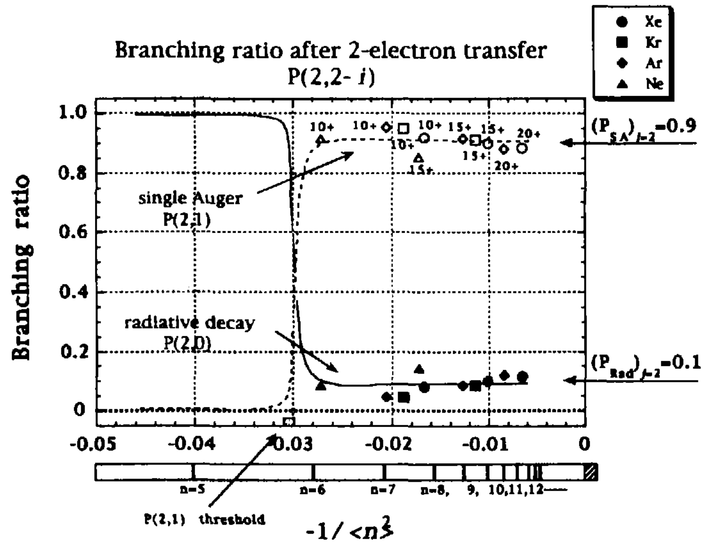

Figure 1. $-1/\langle n \rangle^2$ dependence of the branching ratios after 2-electron transfer : P(2,2-i). n is the principal quantum number of the transferring excited levels calculated by ECBM

q becomes higher, the highly charged ions capture electrons into higher excitation levels than the threshold ($n_{thre} \cong 5.7$), where the Auger decay becomes energetically possible. In these cases, the single Auger decay becomes dominant and the branching ratios show almost constant value. Actually as shown in our experimental results with charge state range of *q*=10~20, the branching ratio *P(2,1)* has been determined to be 0.9, while the branching ratio of radiative decay *P(2,0)* is about 0.1, indicating that the radiative decay rate is much smaller than the Auger decay rate.

B) Triply-excited states

In the triply-excited states (figure 2), when three electrons are bound to the comparatively deep inner shells ($5.3 \leq \langle n \rangle \leq 6$) of the ion, the excited states of *ions decay dominantly by* emitting one electron. However, when the electrons are transferred to levels higher than the *P(3,2)* threshold level ($n_{thre} \cong 6$), the single Auger decay processes start to decrease, and instead the double Auger decay processes start to increase gradually. When the three electrons are transferred to higher excited states ($\langle n \rangle \geq 8$), the fraction of the double Auger decay reaches up to about 0.8. Finally all of the branching ratios (*P(3,0)*, *P(3,1)* and *P(3,2)*) keeps roughly constant in high $\langle n \rangle$ region, where the radiative decay processes almost disappear and the Auger decay processes become dominant.

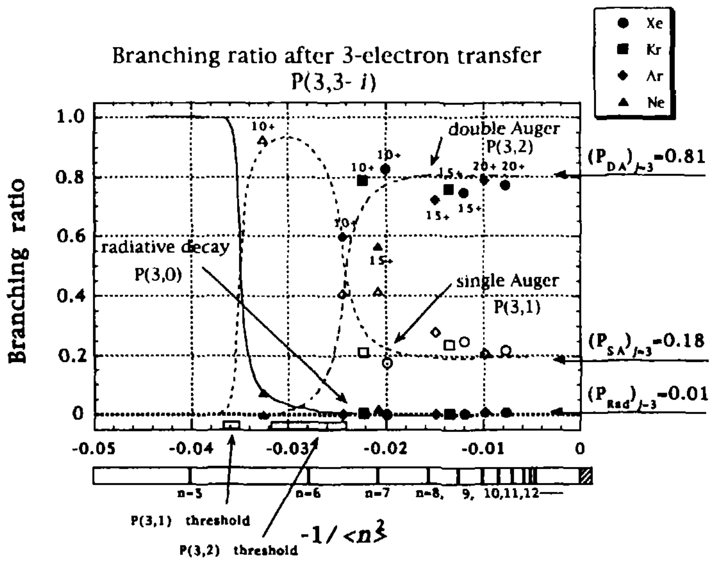

Figure 2. $-1/\langle n \rangle^2$ dependence of the branching ratios after 3-electron transfer : P(3,3-i).

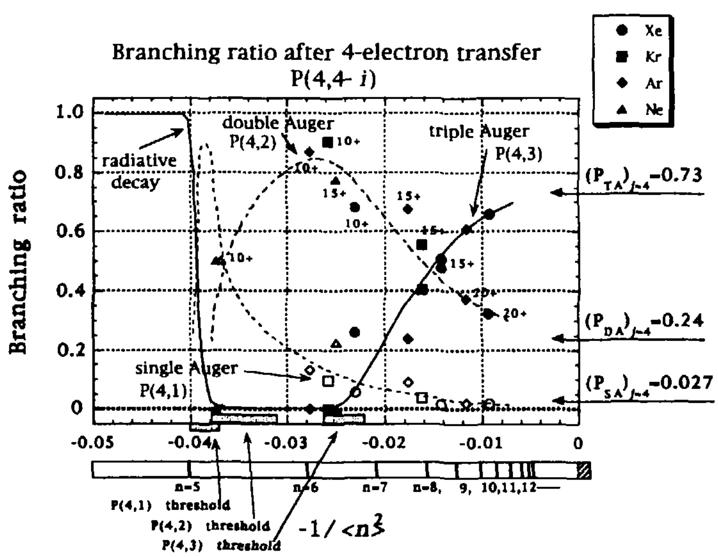

Figure 3. $-1/\langle n \rangle^2$ dependence of the branching ratios after 4-electron transfer : P(4,4-i).

C) Quadruply-excited states

Similarly, in the quadruply-excited states (figure 3), the double Auger decay processes increase as the single Auger decay processes decrease at $<n> \cong 5.3$ and afterwards become dominant at $<n> \cong 6$. The triple Auger decay channel is opened at $<n> \cong 6.3$, the threshold for *P(4,3)*. The ratios of double and triple Auger decays are turned inversely near $<n> \cong 8$. If the four electrons are transferred into still higher excited states ($<n> \geq 11$), the triple Auger decay channels become dominant and the *P(4,3)* approaches to about 0.7.

Through the above arrangements of experimental data, we have summarized the general feature in the decay processes from the multiply-excited states produced by many-electron transfer collisions. When electrons are transferred to higher levels than the threshold $<n_{thre}>$, the Auger decay dominates rather than the radiative decay. Then as the transferred levels go up higher $<n>$, the Auger decay with more than one electron emissions becomes favorable. Finally, all of the branching ratios for radiative and Auger decay processes take constant values as an asymptotic characteristics with high $<n>$.

We will discuss the observed systematic behavior for the decay processes of highly excited ions with multi-Rydberg electrons. At first, we define R_{Auger} as the decay probability with single Auger electron emission and R_{rad} as the radiative decay probability, respectively, from sufficiently high $<n>$ levels produced by the multi-electron transfer, where $R_{Auger} + R_{rad} = 1$. For the doubly-excited states with $<n>$ higher than the threshold level n_{thre}=5.7, the branching ratios, *P(2,1)* and *P(2,0)* become constant and are 0.9 and 0.1, respectively, as shown in figure 1. Therefore, the R_{Auger} corresponds to the asymptotic value of the branching ratio for the single Auger electron decay from the doubly-excited state produced by two-electron transfer (*j*=2) collision: $(P_{SA})_{j=2}$ = *P(2,1)*, and the R_{rad} also corresponds to the branching ratio for the radiative decay: $(P_{rad})_{j=2}$ = *P(2,0)*, which are determined experimentally as follows:

$$(P_{SA})_{j=2} = R_{Auger} = 0.9, \quad (P_{rad})_{j=2} = R_{rad} = 0.1.$$

In three and four-electron transfer collisions, triply- and quadruply-excited states can be produced, which may decay radiatively and ejecting two or three electrons. Here, we make assumptions that, for the multiply-excited states with asymptotically high $<n>$, the successive Auger decay processes are favorable, which take place successively with combination of cascading single Auger processes, whose probabilities are nearly the same because the multi-electrons still remain in high Rydberg states after the first and the succeeding Auger decay processes. On the other hand, we suppose that the multi-Auger decay processes ejecting correlated two or three electrons simultaneously is negligible.

Next, we discuss the decay processes from the triply-excited states with high $<n>$. There are three possible processes with own branching ratios, 1) the successive double Auger decay:

$(P_{DA})_{j=3}$, 2) the combination of single Auger and radiative decay: $(P_{SA})_{j=3}$ and 3) the combination of two pure radiative decay: $(P_{rad})_{j=3}$. Based on the above assumptions, the respective branching ratios are expressed as follows:

$$(P_{DA})_{j=3} = (R_{Auger})^2,$$

$$(P_{SA})_{j=3} = 2\times R_{Auger}\times R_{rad} = 2\times R_{Auger}\times(1- R_{Auger}),$$

$$(P_{rad})_{j=3} = (R_{rad})^2=(1- R_{Auger})^2.$$

As the asymptotic value of R_{Auger} has been found to be 0.9 from our experiment, the above branching rations are calculated to be $(P_{DA})_{j=3}$= 0.81, $(P_{SA})_{j=3}$= 0.18 and $(P_{rad})_{j=3}$= 0.01. These values are shown in figure 2 with horizontal arrows. The calculated branching ratios are in good agreement with the asymptotic values in the observations, as seen in figure 2, for three-electron transfer processes.

By extending similar discussion to the decay processes from the quadruply-excited states, the branching ratios of the stabilization probabilities with the triple, double, single Auger and pure radiative decay can be described as follows:

$$(P_{TA})_{j=4} = (R_{Auger})^3,$$

$$(P_{DA})_{j=4} = 3\times(R_{Auger})^2\times R_{rad} = 3\times(R_{Auger})^2\times(1- R_{Auger}),$$

$$(P_{SA})_{j=4} = 3\times R_{Auger}\times(R_{rad})^2 = 3\times R_{Auger}\times(1- R_{Auger})^2,$$

$$(P_{rad})_{j=4} = (R_{rad})^3 = (1- R_{Auger})^3.$$

The calculated values are $(P_{TA})_{j=4}$=0.73, $(P_{DA})_{j=4}$=0.24, $(P_{SA})_{j=4}$=0.027 and $(P_{rad})_{j=4}$=0.001, respectively. These values are shown in figure 3 and again found to reproduce the observed values.

3. Conclusions.

The present observation of branching ratios suggests that the Auger decay processes after multiple electron transfer are characterized by the principal quantum number n of the transferred level and are nearly independent of the projectile ion charge q for q=10~20 range. Asymptotic characteristics of the branching ratios for the related decay modes are described as a combination of successive Auger processes, and well reproduced in terms of the probability determined in the observation of decay processes from the doubly-excited ions with asymptotically high Rydberg electrons. We have found that the branching ratios in high Rydberg states formed in multi-electron transfer processes can be expressed in terms of the decay probability (R_{Auger}) for one Auger electron emission.

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