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LETTER TO THE EDITOR

State-selective differential cross sections of electron capture in 10 MeV Ar^{8+}–He collisions

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Abstract. The single-electron capture processes in collisions of Ar^{8+} ions with He atoms have been studied at a collision velocity of 3.17 atomic units (au) through a state-selective measurement of differential cross sections. Cold-target recoil-ion momentum spectroscopy (COLTRIMS) has been employed to identify the final state of the captured electron and the momentum transfer between the collision partners. Relative differential cross sections for the capture to 3s, 3p $n = 4$, and $n = 5$ orbitals of Ar ions are obtained and are in qualitative agreement with a semiclassical close-coupling calculation using the molecular-state expansion method. The electron is dominantly captured to the $n = 5$ orbitals, which is in accordance with recent observations at lower velocities.

Electron transfer processes in collisions between highly charged ions (charge $q+$) and light atoms have different features depending on the collision velocity and ion species. In slow collisions where the nuclear collision velocity v is lower than the orbital velocity of the slowest electrons in the system ($v < 1$ au), the electron capture process can be described reasonably well by a transition between quasi-molecular states formed during the collision. In these cases the capture cross section is known to depend weakly on the collision velocity v and the final state of the captured electron is distributed among a small number of states with high principal quantum number n.

On the other hand, in fast collisions where v is larger than the electron velocity, the electron capture is described within the framework of various first-order perturbation theories. The electron capture cross section is determined by the overlap between the momentum-space wavefunctions of the initial and final states and shows a steep decrease as a function of the velocity. The final state of the captured electron is expected to be the ground state.

In the intermediate region the collision process is more complicated where the coupling between different channels becomes important in the electronic transitions. In this case the final state of the captured electron is distributed among many states and this distribution depends on the collision velocity. Close-coupling calculations incorporating a large number of basis functions are essential to describe these collisions correctly.

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For a detailed study of the electron-capture processes, it is useful to measure the electron transfer cross section as differentially as possible. The final-state selective differential cross section as a function of the projectile scattering angle is directly related to the transition amplitude between the initial and each final state and hence it is decisive for the theoretical model. However, such measurements have been difficult at intermediate and high velocities, especially for highly charged heavy ion projectiles, where the ratio of the momentum transfer to the total collision momentum and thus the scattering angle of interest are very small to be measured directly. Recently, cold-target recoil-ion momentum spectroscopy (COLTRIMS) [1, 2], has enabled very high resolution differential measurements of the cross sections over a wide range of projectiles and velocities. Mergel *et al* [3] reported the first COLTRIMS measurements of differential cross sections for single-electron capture to the ground and excited states in $He^+ + He$ collisions at projectile energies from 0.25 to 1 MeV. Cassimi *et al* [4] studied state-selective electron capture in a slower system; 6.82 keV u^{-1} Ne^{10+} and 6.75 keV u^{-1} Ar^{18+} on He. We have reported several measurements of state-selective differential cross sections of electron capture from He by 0.567 MeV u^{-1} O^{7+} [5] and 0.5–1 MeV u^{-1} $B^{4+,5+}$ [6]. Our former results were compared with calculations of a close-coupling calculation and the latter with an eikonal approximation.

Here we report on measurements of the final-state selective differential cross section for a multi-electron collision system at an intermediate velocity (3.17 au) with a 10 MeV Ar^{8+} ion on a He target:

$$Ar^{8+}(1s^2 2s^2 2p^6) + He(1s^2) \rightarrow Ar^{7+}(1s^2 2s^2 2p^6 nl) + He^+. \qquad (1)$$

Since an Ar^{8+} ion has a neon-like electron configuration, the electron can be captured to a $n = 3$ or a higher orbital. In the multi-electron projectile, the energy separation between substates with the same n and different l is large enough to be analysed by COLTRIMS. The substate dependence of the differential cross section is useful for a more detailed study of the capture process. Recently, Abdallah *et al* [7] have studied the electron capture process in this collision system at velocities between 0.2 and 1.0 au. Using COLTRIMS, they have measured the final n and l distribution of the captured electron and the angular distribution. They have found that at velocities below 0.5 au the final state distribution of the captured electrons is dominated by $n = 4$ states in fair agreement with Landau–Zener (LZ) theory. However, at higher velocity, the higher n states are populated in clear contrast to the prediction of the LZ theory. Our collision velocity is more than three times higher than theirs and it is interesting to see whether the final state distribution still shifts to higher n at this velocity.

We have measured the longitudinal component (parallel to the projectile momentum) ($p_{\parallel R}$) and the transverse component ($p_{\perp R}$) of the recoil He^+ ion momentum applying COLTRIMS in coincidence with the projectile which captures one electron. From the analyses of $p_{\parallel R}$ we have obtained the kinetic energy gain which corresponds to the final state of the captured electron, whereas $p_{\perp R}$ corresponds to the scattering angle. Thus differential cross sections are obtained for each final state as a function of the scattering angle.

The experimental set-up at the heavy-ion linear accelerator of RIKEN was described previously [5, 6]. With optimization of the extraction field distribution, the resolution of the recoil-ion momentum was about 0.2 au in all directions, which corresponds to a resolution of 17 eV in the binding energy of the captured electron, and of 0.9 μrad in the scattering angle.

Figure 1 shows the longitudinal recoil-ion momentum $p_{\parallel R}$ distribution by Ar^{8+} ions where the yield is integrated over $p_{\perp R}$ between 0 and 4 au. The excitation energies of the

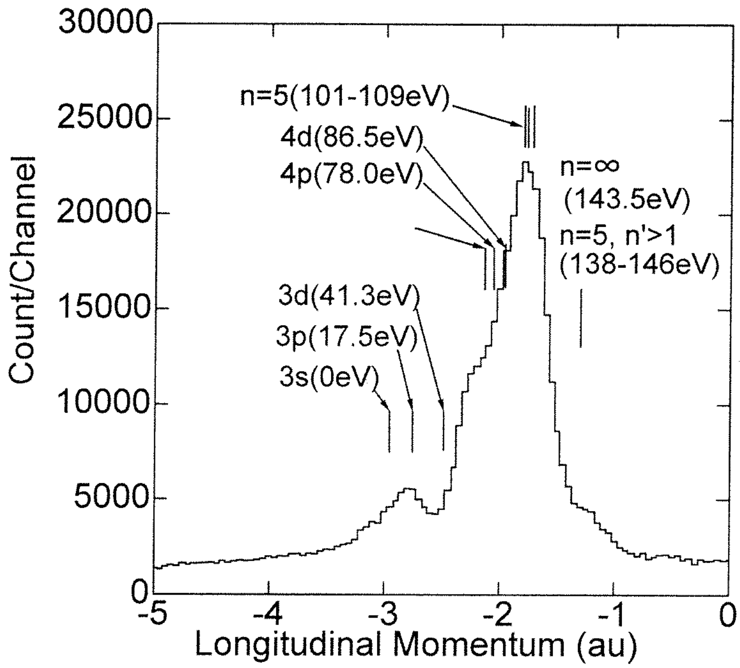

Figure 1. The longitudinal momentum distribution of the recoil ions for one-electron capture from He by 0.25 MeV u^{-1} Ar^{8+} ions. The recoil-ion yield is integrated over the transverse momentum between 0 and 4 au. The electronic states of the captured electron and their excitation energies are also indicated.

final states of the Ar^{7+} ion are also shown in the figure. The final states of the captured electron in $Ar^{7+}(nl)$ with $n = 3, 4, 5$ were separated from the longitudinal momentum of the recoil ions. The capture to the $n = 4$ state was observed as a shoulder on the left-hand side of the peak due to the capture to the $n = 5$ state. The electron capture predominantly occurs into the $n = 5$ orbital, followed by the $n = 4$ and 3 orbitals. This shows that the increase of the $n = 5$ population observed at lower velocities [7] keeps on at the higher velocity region. It is surprising since at still higher velocities the electron is believed to be dominantly captured to the ground state due to velocity matching.

Since the 3s state is separated from the 3p by only 17 eV, the two lines could not be resolved as separated peaks, but the 3s line can be observed as a shoulder on the 3p peak. The capture to the 3d state was not seen since it was too close to the $n = 4$ states. The observed energy gain resolution relative to the total projectile energy is about 2×10^{-6}. It should be noted that simultaneously with the capture process the second electron of He can be excited to the $n = 2$ or higher states which is called transfer excitation (TE). This results in a shift of the recoil longitudinal momentum of the electron capture towards the forward direction by about 0.47 au relative to those with He^{+} in the ground state. This explains the small shoulder in figure 1 at about -1.1 au which may correspond to the capture to the Ar $n = 5$ state with the recoil He^{+} in the excited states. The peaks of $n = 4$ and 5 may be contaminated by the TE with lower n but we consider that this contribution is small.

As shown in figure 2 the relative intensities among different final states vary with $p_{\perp R}$: the fraction of $n = 5$ is predominant at small $p_{\perp R}$ but the fraction of $n = 3$ and 4 increases with $p_{\perp R}$. To obtain the $p_{\perp R}$-dependent differential cross sections of electron capture to

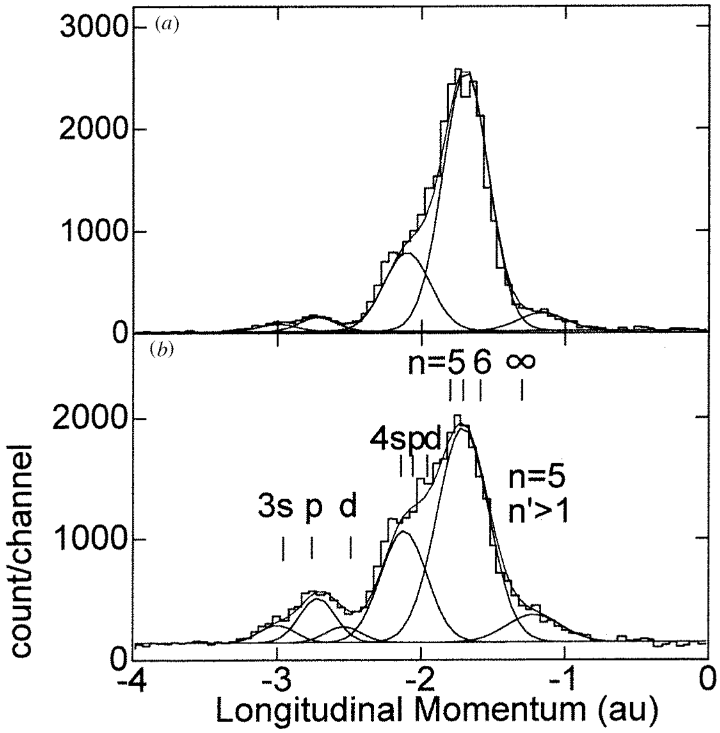

Figure 2. The longitudinal momentum distribution of the recoil ions from one-electron capture in different transverse momentum ($p_{\perp R}$) regions: (*a*) between 0.25 and 0.5 au and (*b*) between 2 and 2.5 au. The results of the Gaussian fit are also shown along with the final states of the electron capture from He into Ar^{7+}.

the different states, we have fitted the $p_{\parallel R}$ distributions in different $p_{\perp R}$ regions by a sum of Gaussian peaks which correspond to the final states of 3s, 3p, 3d, $n = 4$, 5, and an additional peak at about -1.1 au which is attributed to the TE process leaving an excited recoil He^+ ion.

Figure 3 shows the relative differential cross sections $d\sigma/dp_{\perp R}$ of single-electron capture to the $n = 3$–5 states as functions of $p_{\perp R}$. The $p_{\perp R}$ dependence of the capture cross sections to the $n = 3$–5 states have a peak at small $p_{\perp R}$, around 0.7–1 au. At higher $p_{\perp R}$ they decrease monotonically, with a steeper slope for the higher excited state.

The relative differential cross sections to the substates of $n = 3$, the 3s and 3p, are shown in figure 4. The cross section to the 3d state is not shown in the figure since the relative uncertainty is high although it was included in the peak-fit analyses.

The experimental results of the differential cross sections are compared with calculations of the close-coupling approximation based on a molecular representation which is described in more detail below. The experimental results are normalized with a common multiplication factor, so that the total yield summed over $n = 3$–5 states and integrated over the transverse momentum up to 4 au is equal to the corresponding theoretical value.

We have employed the configuration-interaction (CI) method to obtain molecular electronic states of the collision system [8, 9]. The pseudopotential method was adopted to represent the Ar^{8+} core, which enables us to reduce the many-electron system to a more tractable two-electron system. The Slater-type orbitals were used to construct basis sets and

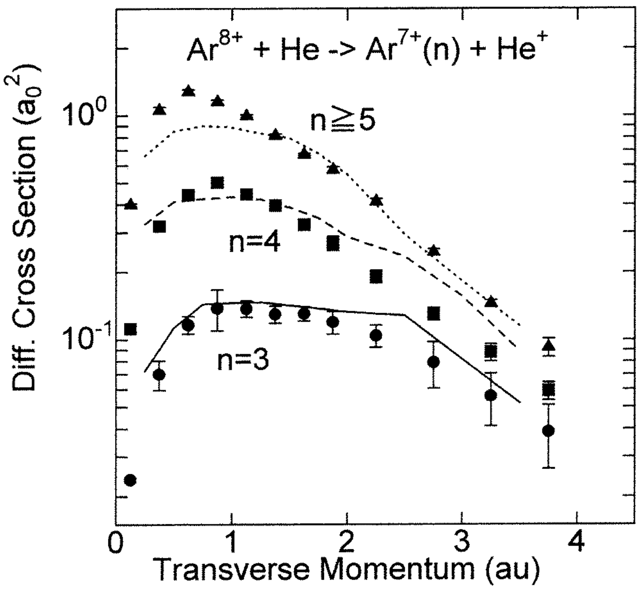

Figure 3. The differential cross section for the one-electron capture from He to $n = 3$–5 states of Ar^{7+} as a function of $p_{\perp R}$. Symbols denote the experimental results and curves are the calculation results.

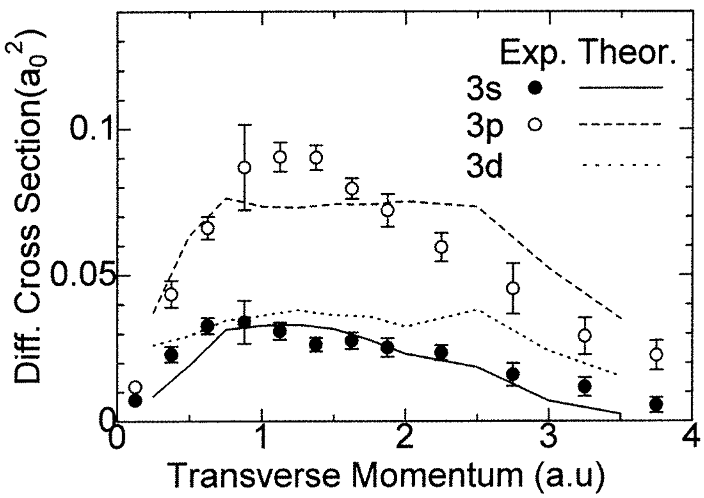

Figure 4. Differential cross section of one-electron capture by 10 MeV Ar^{8+} ions into $n = 3$ substates. Symbols denote the experimental results for 3s and 3p, and curves are the calculation results for all the $n = 3$ substates.

Slater exponents were given previously [8]. The present level of precision of all electronic states considered is within less than 2% compared to experimental asymptotic levels. All states corresponding to Ar^{7+} ($n = 3$, 4 and 5; $l = n - 1$) were obtained. The series of avoided crossings between the initial Ar^{8+}/He channel and the $Ar^{7+}(n = 5)/He^{+}$,

$Ar^{7+}(n = 4)/He^+$ and $Ar^{7+}(n = 3)/He^+$ levels take places around 8, 7 and 5.5 au, respectively, and these crossings play a key role for capture processes depending upon the collision energy. Generally, because of the more diabatic nature for the higher l-state at curve crossings, p and d states are found to be dominant states for capture.

The results of the calculation are shown in figure 3 by curves. In the present collision energy regime, $Ar^{7+}(n = 5)$ channels predominantly contribute to capture, followed by $n = 4$ and then $n = 3$ manifolds. All cross sections have a peak, but it shifts to larger transverse momentum as capture state n decreases from $n = 5$ to 3. The peak position is found to be around 0.7 au for $Ar^{7+}(n = 5)$, 1.0 au for $n = 4$ and 1.2 au for $n = 3$, respectively. This is apparent in connection to the curve-crossing argument. All cross sections decrease as the transverse momentum increases much further, which may be obvious. These features are in good agreement with the experimental data as shown in figure 3.

The $3l$ substate dependence of the capture cross section is also compared to the experiment in figure 4. Because of the diabatic nature of the curve crossing for higher l partial states with the initial channel such as d and f states, capture to the p state is found to be generally dominant, and then the d state follows. For $Ar^{7+}(n = 3)$ formation, the capture to the p state is larger by a factor of two than s and d states. Captures to d and s states are found to be nearly comparable in magnitude in the present theory. The capture to the d state shows some structures as a function of transverse momentum, suggesting a more sensitive nature of the coupling with other states. There are some differences between the theory and experiment in details, but generally the theory is in a reasonable accord with the measurement, and provides a rationale to the observation.

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