State-Selective Electron Capture in Low Velocity Multiply Charged Ion, Helium Collisions

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Recoil ion momentum spectroscopy has been applied to study low energy, state-selective single electron capture by highly charged projectiles. The specific systems investigated are fully stripped 6.82 keV/u Ne^{10+} and 6.75 keV/u Ar^{18+} on He. Measurements of the He^+ recoil ion longitudinal momenta are used to determine the final *n*-state dependence of the captured electron. Simultaneous measurement of the transverse momenta of the recoil ion yields information about the impact parameter dependence of the reaction and the reaction window for electron capture. [S0031-9007(96)00243-8]

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In low energy ion-atom collisions (i.e., projectile speeds smaller than the target electron speed), the dominant target electron removal process is single electron capture. Such collision processes are central to the understanding of fusion plasmas where neutral beams of D, He, and Li are injected into the plasmas. Photon emission from the cascades of the excited ions produced in electron capture from the neutral beams is routinely used to diagnose impurity ion concentrations and their velocity profiles [1–3]. Likewise, many x-ray laser development methods employ electron capture reactions involving highly charged ions to produce the lasing medium [4]. Similarly, x-ray diagnostics of astrophysical photoionized plasmas rely on low energy electron capture cross sections [5]. Essential to these applications and others is the accurate prediction of low energy state-selective electron capture cross sections involving highly charged ions. At present, little experimental state-selective data exist for charge states above 8+ for the most fundamental cases, those involving fully stripped ions. It is the purpose of this Letter to present high resolution, complete final-state momentum distributions for such reactions using the precision inherent in the newly developed experimental technique of recoil ion momentum spectroscopy.

Projectile energy gain spectroscopy is a commonly used technique to measure the inelastic energy transfer (the *Q* value) which is directly connected to the projectile final state [6]. A typical resolution for the energy gain technique is mainly limited by the projectile beam energy spread, resulting in a $\Delta Q/E_P \sim 10^{-4}$, where E_P is the kinetic energy of the projectile [7]. However, cold-target recoil ion momentum spectroscopy is a powerful new technique which has been recently used very successfully to investigate ionization and capture processes at high and medium impact energy [8–11,17]. Simultaneous with the *Q*-value determination is scattering angle information obtained with a 4π detection solid angle efficiency. Turning to collisions at low energy, this technique can be used to accurately perform kinematically complete experiments for capture processes. Since the resolution depends only to second order on the momentum spread of the incoming projectile, it allows one to improve upon the *Q*-value resolution compared to the energy gain method. Also improved is the scattering angle resolution due to the very weak recoil ion momentum. Moreover, the recoil ions carry information from the very first moment of the collision and are not affected by postcollisional effects such as the kinematic broadening due to autoionization of the projectile in the case of multiple electron capture. Hence, this method can be used to investigate which initially populated levels lead to stabilization or autoionization. Finally, due to the 4π detection efficiency, low projectile beam intensity can be employed. This is a tremendous advantage for performing experiments with projectiles that are very difficult to produce such as Ar^{18+}.

In our work, we investigate the state-selective single electron capture from helium by fully stripped projectiles. The reaction under study is

$$A^{q+} + \mathrm{He} \rightarrow A^{(q-1)}(n) + \mathrm{He}\,, \qquad (1)$$

where the fully stripped projectile A^{q+} is 270 keV (6.75 keV/u) Ar^{18+} or 150 keV (6.82 keV/u) Ne^{10+}.

A collision leading to the capture of n_c electrons with no electrons in final continuum states is equivalent to a pure two-body inelastic collision in which a mass transfer (the mass of the captured electrons) occurs between the target and the moving projectile. Momentum and energy conservation laws result readily in the following expression for the longitudinal momentum of the recoiling target $P_\parallel$ (in a.u.):

$$P_\parallel = -\frac{Q}{\nu_P} - \frac{n_c \nu_p}{2}\,, \qquad (2)$$

where ν_P is the projectile velocity. The second term of Eq. (2) corresponds to the mass transfer of the electron from the target to the projectile frame of reference, an effect that was first observed in 1 MeV F^{9+} + Ne collisions

[12]. For single electron capture by a fully stripped ion, the inelastic energy change is simply given by

$$Q = Z_P^2/2n^2 - U, \quad (3)$$

where U is the first ionization potential of the target atom and Z_P is the nuclear charge of the projectile (for a He target, $U = 0.903$ a.u.). Thus, the measurement of the recoil ion's longitudinal momentum yields a direct determination of the final state of the electron capture on the projectile.

In our experiment, fully stripped Ne^{10+} and Ar^{18+} projectile ions are produced by a 14 GHz electron cyclotron resonance source [13]. Details of the experimental arrangement have been described elsewhere [8,14]. Briefly, a 0.6 mm diameter circular incoming beam collides with a supersonic He gas target. The scattered projectile ions are charge state analyzed by a low resolution electrostatic analyzer and are detected on a position sensitive microchannel plate detector. In the collision region, the diameter of the target jet is 1 mm, and its density is about 10^{12} atoms/cm^3 [15]. The transverse velocity distribution of the target atoms in the beam direction corresponds to a temperature of 0.1 K. The He^+ recoil ions are extracted from the interaction region by a homogeneous electric field of 5.5 V/cm, and then enter a field-free region to ensure time focusing [16]. The recoil ions are then postaccelerated to a position sensitive channel plate detector to ensure optimal efficiency. For each scattering event, the acquisition system records the position of the recoil ion in coincidence with its time of flight and the charge state of the projectile ion. For each single electron capture event the x, y, and z components of the recoil ion momentum are determined [8].

The experiment has a recoil ion momentum resolution of 0.4 a.u., which corresponds to a $\Delta Q/E_P$ value of $\sim 2 \times 10^{-5}$, or a ΔQ of ~ 5 eV. With the actually set-up configuration, the resolution is not limited by the recoil ions detector nor by the momentum spread of the target but rather by the width of the supersonic jet. One can increase the resolution by a factor of 2 by reducing the width of the target. Both the longitudinal and transverse momentum of the recoil ion are detected in coincidence. In the transverse direction, the observed momentum has an equivalent angular resolution of ~ 5 μrad. Such a resolution allows the detailed investigation of state-selective electron capture.

Three-dimensional plots of the event files for the longitudinal momentum $P_\parallel$ in coincidence with the transverse momentum $P_\perp$ are shown in Fig. 1 for the Ne^{10+} and Ar^{18+} systems. For the Ne^{10+} + He electron capture system, the experimental resolution is sufficient to easily separate the capture to the $n = 4$ and $n = 5$ states. The $n = 5$ products dominate the reaction, with the maximum contribution to the state-selective total cross section occurring at small recoil ion transverse momenta, or large impact parameters. For Ar^{18+} both the $n = 7$ and $n = 8$ contribute approximately equally to the capture cross section with the $n = 8$ state contributing preferentially at large impact parameters, small recoil ion transverse momenta, while the $n = 7$ dominates for larger transverse momenta, small impact parameter collisions. We observe that all the centroids have negative longitudinal momentum values consistent with what one would expect for exoergic electron capture collisions and that capture to $n = 7$ for the Ar^{18+} reaction possibly exhibits Stueckelberg oscillatory structure.

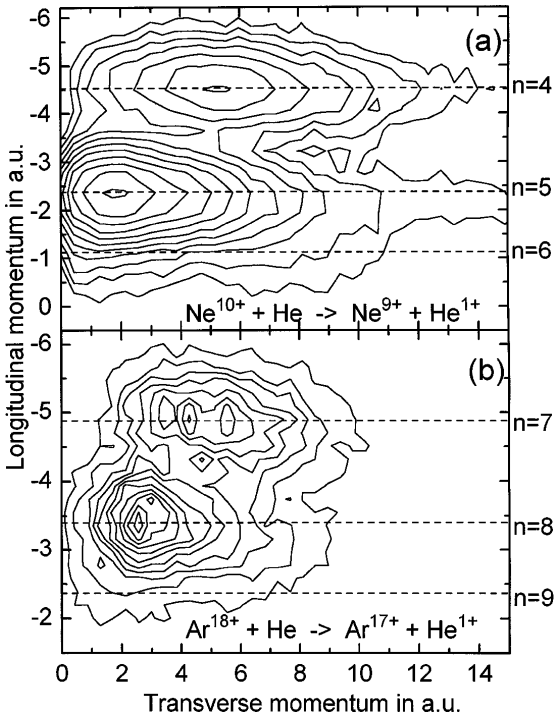

FIG. 1. Experimental coincidence recoil ion distributions of longitudinal versus transverse momenta for the single capture reaction from He by Ne^{10+} (a) and Ar^{18+} (b). Dashed line: calculated position of electron capture to specific n level.

To obtain state-selective cross sections, we have integrated over the transverse momenta and converted the resulting single differential longitudinal momentum distributions to the Q values of the reactions using Eqs. (2) and (3). The results are shown in Fig. 2 for Ne^{10+} and Ar^{18+}, respectively. Gaussian curves have been fit to the data to extract the contribution of the different state-selective products. The fitting procedure is justified by the fact that our Q resolution is mainly limited by the width of the target gas jet whose density profile can be approximated by a Gaussian shape. The half-width of the Gaussians has been derived from the value determined by the width of the gas jet (the same value for all the curves). Their positions have been fixed to the values given by Eqs. (2) and (3). To compare with the data, calculations of the electron capture processes were made using the nCTMC method [18,19]. This method directly includes the scattering dynamics of each

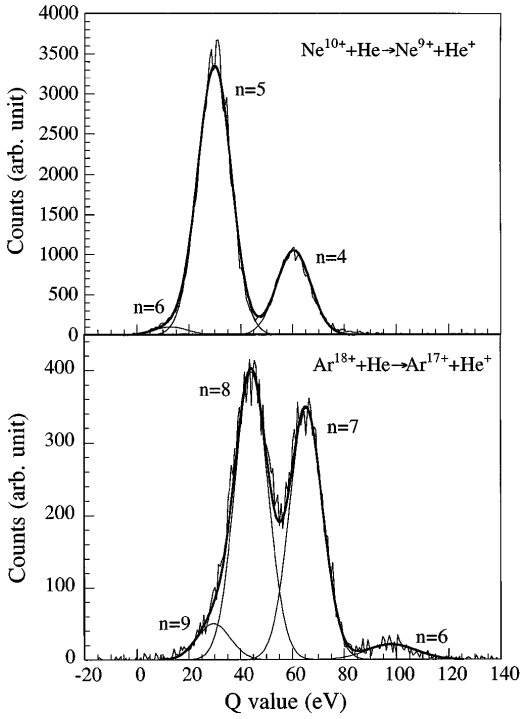

FIG. 2. Experimental Q-value distributions for the Ne^{10+} and Ar^{18+} reactions.

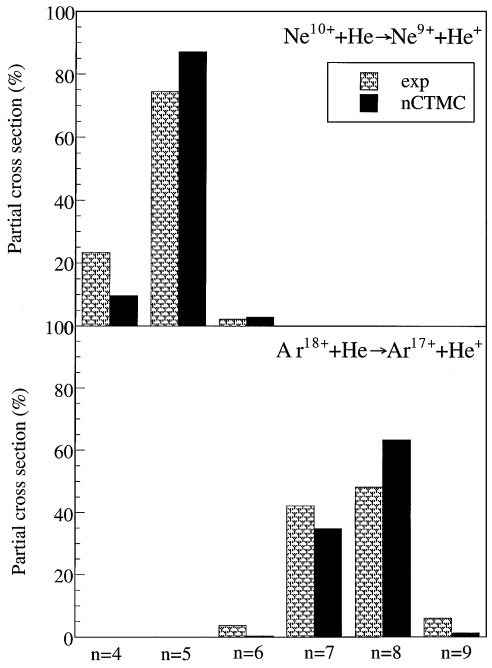

FIG. 3. Comparison of the state-selective cross section contributions given by experiment and nCTMC calculations.

of the four particles (the projectile and the target nuclei, and the two helium electrons) in the collision. Each trajectory is evaluated numerically, and, for every successful electron capture event, the momenta of the recoil ion are recorded and tabulated. After a sufficient number of trajectories, in this case 10^6, a three-dimensional plot is made of the number of capture events versus the recoil ion's longitudinal and transverse momenta.

The calculated state-selective cross section contributions to each product state is directly compared in Fig. 3 to experiment using the integrated (over transverse momenta) longitudinal momentum information. The nCTMC calculations are in reasonable agreement and confirm the validity of the theoretical method. Moreover, at the level tested here the nCTMC method is an exact over-the-barrier model (OBM). The favorable comparison helps confirm the validity of OBM interpretations of electron capture reactions [20]. The nCTMC integral cross sections are 1.5×10^{-15} and 2.2×10^{-15} cm^2 for the Ne^{10+} and Ar^{18+} reactions.

As a further comparison to previous studies, the average quantum number n^* of the electron capture levels can be extracted from the experimental n distribution and compared to theoretical predictions. Within the OBM, the mean value of the n levels populated via electron capture to a fully stripped projectile is given by

$$n^* = \sqrt{2}\,(q/z_t)^{0.75}, \tag{4}$$

where q is the projectile charge and z_t the effective charge of the target atom. Early work by Mann *et al.* [21] using Auger electron and x-ray spectra of electron capture by recoil ions confirmed the general scaling dependence provided by Eq. (4). Later, Tawara *et al.* [22] investigated collisions involving partially stripped I^{q+} ions with charge states $q = 10{-}41$. Although final product states were not resolved, the data were adequate to determine an empirical formula $n^* = 0.76q^{0.818}$. For a comparison of these results against our experimental data we find n^* values of 4.79 and 7.57 for Ne^{10+} and Ar^{18+} which are consistent with that of Tarawa *et al.*, but yield a very slightly different projectile charge state dependence of $q^{0.779}$. The data are also close to the predictions based on classical arguments, Eq. (4), and the nCTMC calculations which yield $q^{0.75}$ and predict n^* values of 4.93 and 7.66 for Ne^{10+} and Ar^{18+}.

Since the impact parameter is not an experimental observable, we have used the nCTMC calculations to find the correspondence between transverse momentum and impact parameter for the two collisional systems under study; results are given in Fig. 4. Because the collision is slow, we note that there is a good correspondence between impact parameter and recoil ion transverse momenta. The width of the distributions relates to the time evolution of the capture reaction as to whether the electron is transferred before or after the distance of closest approach. Referring to the three-dimensional plot for Ne^{10+} given in Fig. 1, we note that the maximum contribution for $n = 5$ and $n = 4$ production occurs at transverse recoil ion momenta of 1.8 and 5.2 a.u., respectively. From the impact parameter versus transverse momenta plot

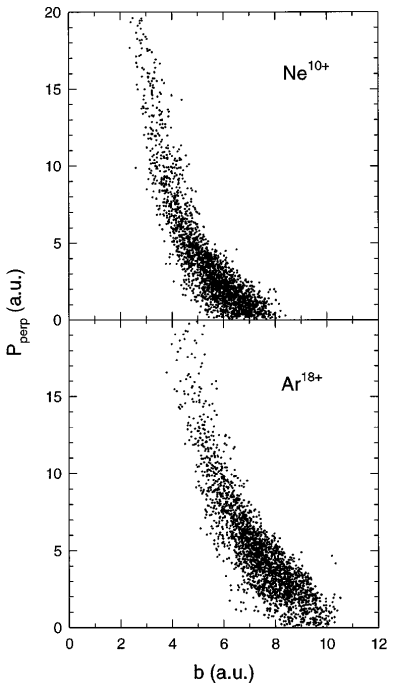

FIG. 4. Calculated impact parameter b versus transverse momentum for the reactions under study.

of Fig. 4, we find these momenta correspond to impact parameters centered around $6.5a_0$ and $4.5a_0$, respectively. Such values are consistent with curve crossing arguments that place the crossing radii at $8.2a_0$ and $4.1a_0$ for the $n = 5$ and $n = 4$ reactions. Similar comparisons can be made for the Ar^{18+} case. Here, the observed maxima for $n = 8$ and $n = 7$ production occur at 2.5 and 5.0 a.u. of transverse recoil ion momenta. These values correspond to impact parameters of approximately $8.5a_0$ and $7.0a_0$. The corresponding radii for curve crossing into the $n = 8$ and $n = 7$ states are $10.4a_0$ and $7.1a_0$, respectively.

In conclusion, we have used recoil momentum spectroscopy to determine Q values and state-selective cross sections for low energy single capture involving highly charged fully stripped projectiles. Coincidence measurements of the transverse and longitudinal momenta of the recoil ion provide additional information about the impact parameter dependence of the reactions. Averaging the measured n-state distributions allows comparisons to existing theoretical models of electron capture. Here, we verify that the n-value peak position varies very closely with the $q^{0.75}$ dependence predicted by the classical over-the-barrier model. Other experiments are still being analyzed and will appear in a forthcoming full paper on the subject.

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