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CONF-800859--1

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MULTIPLE IONIZATION AND EXCITATION PROCESSES IN SINGLE ION-ATOM COLLISIONS.

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The topic of multiple ionization and excitation processes occurring in collisions between highly charged heavy ions and atomic targets has received heavy experimental and theoretical attention for at least the past decade. Much of the activity in the field arose from the increasing availability to atomic physicists of accelerators capable of producing fast beams of highly stripped ions, the wealth of complex phenomena produced by the rapid and transient introduction of extremely large perturbing forces into otherwise stable atomic systems, and a desire to unravel that complexity with simple models. Considerable progress has been made toward cataloging, quantifying, and understanding these processes, but many results are still unexplained and new realms of the atomic structure and collision physics of highly charged ions remain unexplored, awaiting new technologies and daring ideas.

It is far beyond the scope of the present paper to provide a complete review of the many sub-topics that fall into this category; in any case a number of excellent reviews can be found in the book edited by Sellin¹ containing, among other related topics, surveys of electron emission phenomena by Stolterfoht,² x-ray production by Mokler and Folkmann,³ excited state lifetime measurements and production of slow highly charged recoil ions by Sellin⁴ and theoretical aspects of inelastic ion-atom collisions by Briggs and Taulbjerg.⁵ Several older yet quite pertinent and very readable reviews appear in the book edited by Crasemann,⁶ notably the theoretical contribution of Madison and Merzbacher⁷ and the experimental review by Richard.⁸ In an attempt to keep the present work within manageable proportions, I propose to discuss several experimental methods which, by relying on intentionally imposed restrictions such as coincidence

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requirements and/or special detection geometries, permit measurements differential in several important collision parameters. Such multiply differential measurements are necessary for the isolation of particular excitation and ionization mechanisms and, as noted by Eugen Merzbacher⁹ in the 1976 keynote address to this conference, provide much more stringent tests of existing theories. To further limit this discussion, I will concentrate on single collision phenomena involving primarily heavy ions at velocities comparable to K-shell velocities, and will omit any discussion of the important impact parameter dependence studies which form a separate topic session at this conference.

Most of the multiple ionization and excitation of initially neutral targets produced by passage of a highly charged ion at target K velocities occurs in the outer shells; outer-shell processes, in a total cross-section sense, dominate target stripping because of the large impact parameters involved. When, as in the present case, the characteristic response time of outer-shell orbitals is long in comparison with the collision time, the interaction between the projectile and a particular electron to be ionized does not appreciably affect or depend upon the other target electrons, leading to a statistical independent-electron description of multi-electron transition probabilities.^{10, 11} Employing this model in a classical trajectory Monte Carlo method, Olson¹² has calculated multiple ionization cross sections for 1 MeV/amu collisions of multiply-charged ions in the rare gas targets He, Ne, and Ar. A combination of the long-range intense Coulomb field of the ion and very short interaction times gives rise to the production of highly charged slow ($\lesssim 30$ eV) recoiling targets, a fact demonstrated by observation¹³ of Ne Lyman- α radiation as well as decay of various two- and three-electron ions⁺¹⁴ produced in significant quantity in single collisions of 80 MeV Ar with Ne (see Fig. 1) and by the extremely low Doppler broadening of target x-ray and K-Auger lines observed in similar collisions.^{14, 15} Cocke¹⁶ has demonstrated the feasibility of extracting multiply-charged recoil ions from the collision region and performing time-of-flight spectroscopy to determine their distribution in charge state. He finds the production of lower charge states to be in reasonable agreement with the independent electron model of Olson¹² but that higher charge state cross sections are better described by an energy deposition model which accounts for the increased binding and decreased ionization probability of an n th outer-shell electron resulting from the ionization and removal of screening of $n-1$ other electrons.

Because extraction efficiencies and production cross sections for slow recoil ions are quite high ($\sim 10^{-16}$ cm²) and because much of the cross section occurs from relatively large impact ($\sim 1-5$ au) parameters, the projectile scattering angles are small and it is possible to efficiently collect and study the scattered projectile

Fig. 1. Neon K x-ray spectrum produced by 80 MeV argon bombardment, showing strong increase of one-, two-, and three-electron target ions with increasing incident projectile charge.

charge state in coincidence with the target recoil ion, as recently demonstrated by Cocke and co-workers.¹⁷ They observe that the mean recoil charge state increases dramatically when the incident projectile becomes K-ionized and when incident bare projectiles experience single and double capture events. Similar phenomena, collectively referred to as projectile charge state effects, have long been observed in K x-ray and Auger emission,^{13, 18} although not under the experimentally clear conditions afforded by the recoil-ion/scattered projectile coincidence technique reported by Cocke et al.¹⁷ Similar experiments using proton projectiles at MeV energies have been reported by Pedersen and Larsen.¹⁹

Secondary experiments using such recoil ions to study charge exchange phenomena involving slow ($\sim 10^{-6}$ cm/sec) highly charged ions, which can remain within view of a spectrometer for times ~ 300 nsec, with various gases have been reported by Beyer et al.,²⁰ and there has been some discussion of extracting recoil ions to form controllable beams of high charge states.^{16, 21}

At smaller impact parameters sufficient to produce K-vacancies in the target and/or projectile, extensive outer-shell stripping and excitation occurs, owing to almost complete penetration of the outer orbitals. In this collision regime, multiple outer-shell vacancy production accompanying K-vacancies has been extensively studied via observation of K x-ray satellite spectra and K-Auger emission,¹⁸ and it has been shown that the probability for L-shell ionization agrees rather well with the binomial statistics predicted by independent electron treatments.^{10, 11} There are unsettled questions, however, about the relationship between the single-electron removal probabilities associated with the binomially distributed multiple ionization probabilities and Coulomb ionization cross sections, particularly in cases where the projectile to target nuclear charge ratios Z_1/Z_2 are not small.¹⁸ This is likely to be a result of projectile capture processes which become important for larger Z_1/Z_2 , as will be discussed shortly. In addition, Reading and Ford²² have shown that the probability for production of two vacancies cannot be taken as the product of single-electron removal probabilities, a feature underlying the binomial model, when the vacancies produced form a spin triplet.

At even smaller impact parameters, for which distances of closest approach are much smaller than characteristic K-shell radii and large projectile scattering angles (~ 5 to 10°) occur, and for targets heavy compared with the projectile, Rosner and Gur²³ have observed a distribution of final projectile charge states which is quite insensitive to the incident charge state. In other words, a charge state equilibrium situation, similar to that produced by multiple collisions in solid targets, is reached in a single collision! These authors discuss their results in terms of a qualitative model containing features in common with the energy-deposition model of Cocke,¹⁶ but with substantial decoupling between incoming and outgoing channels, so that for heavy targets with many outer-shell electrons, electrons brought into the collision by the projectile do not substantially alter the statistical process whereby the final projectile charge state is determined.

The importance of projectile capture processes to target K-vacancy production, suggested by the projectile charge state effect and demonstrated by the dramatic increase of target K-x-ray flux with the introduction of projectile K vacancies, was very clearly defined by Rdbro et al.²⁴ This experiment extended the earlier and related work with proton projectiles by Cocke et al.²⁵ and Macdonald et al.²⁶ and serves as an excellent example of the utility of coincidence techniques. By measuring K-Auger emissions from C (in methane), Ne, and Ar targets, induced by H^+ , He^{2+} , and Li^{3+} impact, in coincidence with projectiles which underwent a bound-state capture, those workers were able to unambiguously determine the fraction of target K-vacancy production due to projectile capture. Their results, summarized in Fig. 2, show that the K-capture process

Fig. 2. Fraction of K-vacancy production due to projectile capture for several combinations of projectile (Z_1) and target (Z_2) nuclear charges. From Rødbro et al., Ref. 24.

becomes of increasing importance as the ratio of projectile to target charge increases and at projectile velocities near or below the target K-shell velocity.

One experimental approach to the investigation of simultaneous multiple inner- and outer-shell ionization and excitation involves the use of partially stripped (three- and four-electron) projectiles and the study of projectile excitation and ionization subsequent to single collisions with various gas target species. Here again, one can observe either the K x-ray satellite structure produced or K-Auger electrons. Analysis of the x-ray satellite structure is hampered by the need for high-resolution crystal spectrometers (with an attendant loss in collection efficiency) to isolate satellites corresponding to specific production mechanisms, low-efficiency detectors (often requiring severely x-ray energy-dependent window transmission corrections) and small fluorescence yields in the case of three- and four-electron final states containing K vacancies (ω_K between ~ 1 and $\sim 10\%$). Many of these difficulties are avoided if K-Auger electrons are observed instead, with the additional

advantage that uncertainties in small fluorescence yields ω_K are of reduced importance to Auger rates, which depend on $(1 - \omega_K)$. On the other hand, the Auger spectra observed are invariably complicated by overlapping spectra produced by initially excited ions of different charge states, a problem requiring the use of coincidence techniques for resolution.²⁷

A schematic diagram of experimental apparatus especially well suited to the study of projectile excitation and ionization processes as reflected in Auger emission is displayed in Fig. 3. This apparatus employs two major features which are of importance to the study of projectile K-Auger emission: detection of K-Augers at nominally 0° emission angles and coincident final projectile charge-state detection. The first feature takes advantage of the kinematics of projectile frame to laboratory frame transformation to enhance projectile electron emission collection efficiency and eliminate (to first order) kinematic line broadening effects which occur for projectile emission at larger angles. The coincident final charge state detection feature, first used by Groeneveld et al.²⁷ in the study of Ne K-Auger production in multiple collisions with solid foil targets (but at non-zero mean collection angles), has been shown to be of great value in attributing K-Auger structure to particular states of ionization and excitation.

Beyond spectroscopic information such experiments can give information concerning cross sections for a number of single and multiple electron excitation and ionization processes in single K-

Fig. 3. Apparatus used in the study of forward-directed electron emission in coincidence with final projectile charge state and described in the text.

ionizing collisions, since the decays of the excited states of the ions under consideration are usually dominated by Auger emission (small fluorescence yield). The experimental arrangement employed is characterized by a high detection efficiency at charge-state analyzed ion count rates up to 100 KHz. In some cases up to 92% of the total number of Auger-electrons detected could be assigned to a well-defined final charge state by means of this coincidence technique.

Briefly, electrons produced as the result of collisions in a thin (~ 4 mm thick) gas target cell are collected and energy-analyzed by a spherical sector electrostatic analyzer positioned to collect electrons ejected within ~ 2 deg of the forward incident ion direction and with its entrance focus at the center of the target region. Because the Doppler broadening is zero to first order, the energy resolution $\Delta E/E \sim 1.4\%$ observed is characteristic of the analyzer and is not kinematically decided. The projectile beam, negligibly deflected within the electron analyzer, exits the analyzer through a small hole bored in the outer sector and is magnetically dispersed to provide final charge state analysis. As the electron spectrometer deflection voltage is scanned through the energy range of interest, coincidences are sought between energy-analyzed electrons and scattered ions of a particular selected final charge state q' , using a standard time-to-amplitude converter (TAC) arrangement as shown in the figure. As in most coincidence experiments, great care must be taken to maximize true-to-random coincidence ratios by optimizing collection efficiencies and minimizing spurious background events. Thus a quadrupole lens placed between the electron spectrometer and the charge-state analysis magnet can be used to increase the ion collection efficiency by focusing all final ions within ~ 1 deg of the incident direction onto the charge-state selection aperture. In addition, pains have been taken to ensure that ion beams are collimated to much smaller diameters than any apertures near the gas cell and electron spectrometer to minimize the production of secondary electron events unrelated to ion-gas target collisions. Consequently, definition of the electron collection angle and spectrometer resolution is set by the ion beam diameter within the gas cell and a pair of exit apertures in front of the channel electron multiplier. The effectiveness of these measures is evidenced by TAC spectra characterized by a ~ 5 ns FWHM peak and by true/random coincidence ratios usually observed to be $\approx 100:1$.

Exploratory studies using this method have been reported by Suter et al.,²⁸ some results of which are shown in Fig. 4. Analysis of the spectra is facilitated since spectra taken in coincidence with final projectile charge state q' can be associated with an autoionizing state of charge $q'-1$, neglecting the relatively rare events²⁹ involving emission of two simultaneous Auger electrons. Thus for $C^{2+} + Ar$ collisions, the spectrum observed in coincidence with $q' = 3$ (Fig. 4a) exhibits lines from the Be-like ion, presumably

Fig. 4a. Singles and coincidence K-Auger spectra for 19 MeV C^{2+} single collisions with Ar. The coincidence results are labelled with the final projectile charge q' and correspond to emission from initial states with $q_e = q' - 1$. Emission energies are expressed in the projectile rest frame.

4b. As in a, but for 20 MeV O^{4+} in Ar.

formed by a single K-excitation to an outer shell. In making line assignments the detailed experimental and theoretical studies on projectile K-Auger emission from carbon and oxygen ions published by Schneider et al.³⁰ and Bruch et al.³¹ have been of considerable value.

The most intense peak (235-255 eV) in the Be-like spectrum contains several unresolved lines originating from various KLL-Auger transitions in the four-electron ion. A second, much weaker, peak is located at about 280 eV and can be assigned to $(1s2\ell 2\ell' 3\ell'')$ configurations. Approximately $14 \pm 2\%$ of the total number of Auger electrons detected can be attributed to such Be-like transitions arising from single K-excitation processes.

Most (65%) of the singles spectrum appears in coincidence with $q' = 4$, implying Li-like emitters. While the most obvious production mechanism seems to be single K ionization, Tawara et al.³² have observed the single K-vacancy production excitation function for $F^{6+} + He$ collisions in this energy range and find reasonable agreement with a model in which direct K ionization is less important than a two-step process involving an L ionization followed by a $1s-2p$ K excitation. If a similar process occurs in the $C^{2+} + Ar$ system, one would expect a dominance of lines arising from $1s2s2p$ configurations, and this may indeed be the case. In the $q' = 4$ spectrum of Fig. 4a, the lowest lying line at 227 eV can be assigned to transitions from $(1s2s^2)^2S$ terms. The lines of the metastable quartet states $(1s2s2p)^4P$ are only about 2 eV higher, corresponding to less than one channel in the spectrum and cannot be separated from the $(1s2s^2)^2S$ line with the present resolution. Because the electron spectrometer is viewing projectile emission near 0° , a significant portion of the decay path of these metastables can be viewed by the spectrometer (corresponding to 1-2 nsec decay time). The next intense peak at 235 eV can be attributed to $(1s2s2p)^2P^o$ states; in the high-energy tail of this peak, there is structure originating from other $1s2\ell 2\ell'$ configurations. At about 260 eV there is a distinct minimum visible prior to the onset of a weaker, broad structure composed of unresolved lines from $1s2\ell n'\ell'$ ($n' \geq 3$) configurations. The intensity reaches a local maximum at about 274 eV, which coincides best with the energy of the $(1s2s^3S)3d^2D$ states, and drops to near zero around 300 eV, which best matches the 3S series limit.

Because He-like ions only emit Auger electrons if doubly K-excited, coincidence spectra with $q' = 5$ are a direct measure of double K ejection. The feature near 265 eV is attributed to $2\ell 2\ell'$ configurations, and that at ~ 325 eV to $2\ell 3\ell'$ configurations. By comparing the $2\ell 3\ell'$ yields to the $2\ell 2\ell'$ yields, ratios of cross sections for some exotic three-electron processes (double K-electron ejection accompanied by a $2\ell \rightarrow 3\ell'$ excitation) vs. two-electron processes (double K ejection *leaving the L shell undisturbed*) can easily be extracted, with a relative quantitative uncertainty limited only

by inaccuracies in slowly varying electron transmission corrections and by statistics. The He-like Augers account for approximately 16% of total K-Auger production in $C^{2+} + Ar$ collisions.

For a more detailed study of single and double K-vacancy production the optical channel has also to be considered. The fluorescence yields vary with different initial states, and singly excited states of He- and H-like ions can only be detected in the optical channel. High resolution x-ray spectroscopy on the same projectiles is therefore of importance in providing complementary information. Tawara et al.³² have performed this type of measurement with F^{q+} on He, but, because a light target was used, double K-vacancy production was probably small and was not specifically discussed in that work.

A particularly dramatic example of the background suppression afforded by coincident K-Auger and final ion detection is shown in the spectra of Fig. 4b, obtained for 20 MeV O^{4+} ions in Ar. At 20 MeV the projectile K-Auger lines fall in the same spectral region as the binary encounter peak resulting from direct target ionization. Only a tiny fraction of these background electrons are detected in the coincidence spectrum for $q' = 7$, showing clearly that these electrons originate from the target. The two strong peaks in the singles spectrum contain all the lines from $1s2l2l'$ configurations of Li-like ions, and also some KLL lines of Be-like ions. The transitions from higher lying states ($n > 3$) are not well separated from the binary encounter peak and are significantly weaker than the corresponding lines from C^{2+} . The coincidence spectrum clearly shows the advantage of the coincidence technique: Peaks arising from double K-vacancy production, which are 20 times less intense than the background in the singles spectrum and smaller than the statistical fluctuations therein, can easily be recognized in the coincidence spectrum. The feature near 464 ± 3 eV can be assigned to the $2l2l'$ configurations of He-like oxygen, and the peak at 574 eV to $2l3l'$ configurations. The lines from He-like ions contribute about 4% to the total O^{q+} K-Auger electron production at this energy.

For O^{q+} projectiles several interesting comparisons with other experiments can be made. For example, the absolute cross sections for K-Auger production as measured by Stolterfoht et al.³³ permit normalization of the data to obtain absolute Auger production cross sections. With the coincidence data it is possible using the normalized total cross sections to determine individual cross sections for single and multiple electron loss due to Auger processes. A comparison of these cross sections with total electron loss cross sections measured by Macdonald and Martin³⁴ shows that Auger processes can contribute to a large fraction (~ 30 to 40%) of multiple projectile electron loss events, and confirm that Auger processes are important for explaining the previously noted results of Rosner and Gur.²³

The apparatus shown in Fig. 3 was originally developed to study the process known as electron capture to the continuum (ECC), in which the projectile captures a target electron into a final unbound state characterized by an electron emission velocity $\vec{v}_e$ close to that of the ion, $\vec{v}_i$. Early descriptions of this effect were advanced by Salin³⁵ and Macek³⁶ to explain the forward electron emission peak observed by Rudd et al.³⁷ and later confirmed in the work of Crooks and Rudd.³⁸ A theoretical description can be found in the recent article by Shakeshaft and Spruch³⁹ and references to early experimental work in Vane et al.⁴⁰

Since ECC electrons have a small velocity in the rest frame of the capturing ion, it is necessary to consider such final states as Coulomb waves centered on the projectile. This small relative velocity also gives rise to ejection of ECC electrons in the laboratory frame within a narrow cone centered on the forward (incident projectile) direction. The influence of the projectile charge, through a Coulomb wave normalization factor, produces a cusped peak in the forward doubly differential electron emission cross section, centered at an electron emission velocity equal to that of the projectile. Sample ECC cusp spectra are shown in Fig. 5 for 2.5 MeV/u bare O^{q+} and Si^{q+} projectiles in Ar. Also shown for comparison are peaks produced by projectile loss from projectiles carrying electrons into the collision. The projectile loss peaks are roughly an order of magnitude more intense than the ECC cusp, and contain structure attributable to low-energy Auger emission.⁴¹ Note the strong asymmetry of the bare projectile (ECC) cusps.

Fig. 5. The forward peak produced by 2.5 MeV/u O^{q+} and Si^{q+} ions in Ar, labelled by the incident charge state. The individual spectra have been normalized to equal peak intensities to permit comparison of shapes.

The ECC process has, at the time of this writing, been theoretically described only for hydrogenic targets,^{35, 36, 39, 42} and then under approximations which render the results valid only for projectile velocities large compared with target shell velocities. Under these conditions, the asymmetric spectral shape of the forward ECC cusp has been shown⁴³ to be the result of a double-scattering mechanism described by the second Born approximation. A similar mechanism dominates bound-state electron capture at high velocities.⁴² In oversimplified terms, the electron to be captured is ionized from the target in a primary scattering; a second scattering from the target nucleus serves to redirect the ionized electron into the forward direction. The signature of the second Born double-scattering process is the introduction of skewness to the cusp spectral shape, arising from capture into high angular momentum Coulomb continuum states. The complication introduced by multi-electron targets is the opening of further double scattering channels arising from electron-electron scattering, and the possibility of capture from several target shells.

The relevance of the ECC process to the production of multiple target ionization by highly charged projectiles follows from a recently reported experiment⁴⁴ in which the ECC process was detected in coincidence with the final projectile charge state, using the apparatus shown in Fig. 3. For 20 MeV O^{8+} ions in Ar targets under single collision conditions, production of an ECC electron was accompanied by a simultaneous bound-state capture (ECB) roughly one quarter of the time, and by *two* simultaneous bound-state captures approximately 10% of the time. Because of the small solid angle sampled in this experiment, not all ECC events were detected. By assuming that the doubly differential (in emission angle and velocity) ECC cross section is correctly described by the analytic form developed by Dettmann et al.,⁴² it is possible to estimate from the data a total cross section associated with simultaneous electron capture to the continuum and $0 \leq n \leq 3$ bound-state captures. By comparing these total cross sections with total bound-state capture cross sections for the same velocity oxygen ions in argon, obtained by MacDonald and Martin,³⁴ it is seen that an ECC event occurs in about 20% of all single, double, and triple bound-state capture events. The differential cross section for simultaneous ECC and bound capture is displayed in Fig. 6 for 20 and 30 MeV O^{8+} ($v_i \sim 7$ au and 9 au, respectively) and 19 MeV C^{6+} ($v_i \sim 8$ au), averaged over a cone of half angle $\theta_0 = 1.6^\circ$ centered on 0° and integrated over velocity intervals $v_e = v_i (1 \pm \alpha)$, $\alpha = 0.04$. The trends evident from the figure suggest that simultaneous ECC and bound capture increases in likelihood as the projectile charge increases and as the collision velocity decreases.

Bound-state capture processes are known to be dominated by capture from the target shell whose characteristic velocity ($[2I_n]^{1/2}$ in au) most nearly matches the projectile velocity.²⁴ Evidence

that this is also the case for continuum capture can be seen in the work of Rødbro and Andersen,⁴⁵ who studied the ECC process for protons in various gas targets, and in the work of Vane⁴⁶ for more highly charged bare ions in neon. Data from the latter are shown in Fig. 7 for the ECC cusp yield as a function of O^{8+} ion velocity in neon and argon gas. It can be seen that near the neon K-shell matching velocity (~ 8 au), the neon cusp yield contains structure similar to that observed by Rødbro and Andersen. This behavior does not occur in the same impact velocity range for He or Ar targets, suggesting that the effect is target-specific and strengthening the argument for a shell-matching phenomenon. In the same velocity region over which Ne K-velocity matching is approximated, the neon cusp spectra display an anomalously large skewness to lower ejected electron velocities, a feature which again is not shared by the He or Ar spectra (Fig. 8). If, as the data suggest, the ECC process can contribute to capture from the target K-shell under velocity-matching conditions, it becomes of interest to estimate the total ECC cross section for comparison with target K-capture cross sections. The ECC result from Fig. 7, obtained as described earlier

Fig. 7. Impact velocity dependence of the total ECC differential cross section for fully stripped O^{8+} projectiles in Ne and Ar, averaged over a cone of semi-angle $\theta_0 = 1.8^\circ$ centered on $\theta = 0^\circ$ and integrated over a velocity interval $v_e = v_1 (1 \pm \alpha)$, with $\alpha = 0.04$.

Fig. 8. Half-widths at half-maximum for the low emission velocity (Γ_L) and high velocity (Γ_R) sides of the ECC peak as a function of incident O^{8+} ion velocity in He, Ne and Ar targets.

for ECC-ECB coincidence results, is $\sigma_K, ECC \sim 3 \times 10^{-18} \text{ cm}^2$, with an uncertainty of about 50%. The most appropriate target K capture cross section available appears to be one derived by Lin⁴⁷ from the work of Woods et al.,⁴⁸ who studied target K-Auger production in $O^{8+} + \text{Ne}$ collisions; that result is $\sigma_K, ECB \sim 3.3 \times 10^{-18} \text{ cm}^2$ with a likely uncertainty of 25%.

The experimental evidence thus suggests that continuum capture from target K shells may compete with electron capture to bound projectile states. Of course, a definitive test will require detection of target K-vacancy production coincident with continuum electron capture. This result is surprising in light of a result obtained by Lapicki and Losonsky⁴⁹ what, within the OBK approximation, continuum capture should decrease relative to bound capture as Z_1^{-3} . In this connection, it is appropriate to mention a contrary suggestion made by Bottcher⁵⁰ - in an attempt to explain, for example, the simultaneous ten-electron transition events observed in high-velocity collisions of bare Ar ions with Ne targets¹³ - that multiple electron capture to projectile-centered continuum might be a dominant channel for the many electron stripping in collisions at high velocity ($v \gtrsim v_K$) collisions involving projectiles of Z_1 comparable to or in excess of the target Z_2 . It is very likely, however, that

multiple ECC events would result in a large scatter in phase space, resulting from mutual Coulomb repulsion, away from the $\vec{v}_e \sim \vec{v}_i$ condition needed to form a cusp. In any event, a complete assessment of the role played by ECC in inner-shell and multiple ionization processes awaits better experimental and theoretical description, particularly under velocity-matching conditions, of the cusp distribution in emission velocity and angle, knowledge of which is necessary for conversion of the inherently differential measurements to total cross sections.

I would like to gratefully acknowledge support from the U. S. National Science Foundation, the U. S. Office of Naval Research, and the U. S. Department of Energy, Division of Basic Energy Sciences, under contract W-7405-eng-26 with the Union Carbide Corporation. Thanks are especially due to my colleagues I. A. Sellin, C. R. Vane, M. Suter, R. Laubert, G. D. Alton, and R. S. Thoe, who have all contributed heavily to our experimental program at ORNL, and to P. Shakeshaft and C. Bottcher for many stimulating discussions.

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