CONVOY ELECTRON PRODUCTION IN HEAVY-ION-SOLID COLLISIONS*

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The properties of the sharp $\vec{v}_e \approx \vec{v}$ cusps observed in the velocity spectrum of convoy electrons ($\vec{v}_e$) ejected in heavy ion-solid collisions in the ion velocity range ($\vec{v}$) 6-18 au are compared to the properties of analogous cusps observed in binary electron capture to the continuum (ECC) and electron loss to the continuum (ELC) collisions in gases. Apart from a skew toward $\vec{v}_e > \vec{v}$, the v-independent convoy distributions observed are very similar to those for ELC and the cusp widths are the same in both cases. While the shape of convoy peaks is approximately independent of projectile Z, v, and of target material, yields in polycrystalline targets (C, Al, Ag, Au) exhibit a strong dependence on Z and v. Coincidence experiments in which convoy electrons are allocated according to emergent ion charge-state q_e show a surprising independence of q_e , mirroring the unweighted statistical emergent charge-state fraction. Coincidence experiments on $0^{6+,7+,8+}$ ions

* Research partially supported by the National Science Foundation; the Office of Naval Research; the Fundamental Interactions Branch, Division of Chemical Sciences, Office of Basic Energy Sciences, U. S. Department of Energy, under contract W-7405-eng-26; and the East Carolina Research Council.

† Deceased. The co-authors of this paper dedicate it to our honored colleague and friend whose many valuable contributions to the literature on atomic collisions in solids will be long remembered.

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traversing $\langle 110 \rangle$ and $\langle 100 \rangle$ channels in Au show a strong yield suppression and a dependence of yield on the channel chosen. Interpretation of these observations, comparisons to convoy production studies using protons, and a discussion of remaining puzzles is given. The history of ECC, ELC, and "wake-riding" models of convoy electron production is also reviewed.

1. Connection between electron capture and loss to continuum states in ion-atom collisions and convoy electron production in ion-solid collisions

At the Eighth International Conference on Atomic Collisions in Solids, Roman Laubert analyzed some results¹ from the first experiments² concerning convoy electron production by fast heavy ions traversing solid targets. Pioneering work for light ions (p, He) traversing solid targets had been initiated earlier by Harrison and Lucas.³ The term "convoy electrons" refers to those electrons emergent from ion-solid collisions closely matching the emergent ion in speed and direction.

The velocity distribution of electrons ejected in both ion-atom and ion-solid collisions into a small cone of half angle θ_0 about the forward direction exhibits a cusp when the outgoing electron velocity v_e matches the velocity v of the incident ions. In ion-atom collisions, electrons with laboratory velocities close to the beam velocity are produced in three major processes:

(a) Projectile electrons are ionized to continuum states of low momentum with respect to the projectile nucleus, a process referred to as electron loss to the continuum (ELC).

(b) Electrons are transferred from a bound state of the target nucleus to a low-lying continuum state of the projectile nucleus. This charge transfer process is referred to as electron capture to the continuum (ECC).

(c) Low rest-frame energy electrons from projectile Auger processes⁴

appear near $v_e = v$ in the laboratory frame.

In gases, bare projectile ions produce only ECC electrons. For 5-18 au C^{6+} , O^{8+} , Si^{14+} and Ar^{18+} projectiles traversing Ar, Ne and He targets, asymmetric cusps in the ECC velocity distribution are observed, peaked at $v_e = v$ and dropping off sharply on the high-velocity side.^{5,6} The ECC cusp width (FWHM) is roughly proportional to v as predicted by the ECC theory of Dettmann et al.,⁷ apart from strong target-shell effects.⁸ The cross section for ECC electron production is found to increase with projectile nuclear charge roughly as $Z^{2.2}$.⁹

If projectiles with loosely bound electrons and therefore lower incident charge states are used, the cross section for ELC in gases greatly exceeds the ECC cross section in the velocity range discussed here.⁵ Again, cusps in the electron velocity distribution, centered at $v_e = v$, are observed. For the same projectile velocities, however, the ELC cusps are nearly symmetric and much narrower than the corresponding ECC cusps.^{9,10} These results are not at all in accord with recent theoretical predictions¹¹ predating those of Day¹² and severely constrain Day's theory. In the wings of certain ELC cusps, low-energy autoionization lines are observed.¹⁰

In discussing such forward electron ejection in ion-solid collisions, it is essential to examine the role of individual binary ion-atom collision encounters. But the situation for convoy electron production in solids is more complex, representing a blend of binary atomic collision phenomena such as ECC and ELC with sharply distinct condensed matter interaction effects. Secondary scattering of convoy electrons inside solids is an example of such an effect.

In his 1979 conference paper, Laubert focused on the yield of convoy electrons emitted in the forward direction from solid targets of C ($30 \mu g/cm^2$),

Al ($50 \mu\text{g}/\text{cm}^2$), Ag ($100 \mu\text{g}/\text{cm}^2$), and Au ($100 \mu\text{g}/\text{cm}^2$) per incident 1-4 MeV/amu H, O, Si and Ni projectile. As expected, the yield is independent of target thickness and of the incident projectile charge state. The yield is target (Z_T) dependent, increases as $Z^{2.75}$ (Z is the atomic number of the incident projectile), and decreases as $E^{-2.25}$ (E is the incident projectile energy in MeV/u).

Figure 2 of Ref. 1 summarizes the estimated total yield of convoy electrons Y in units of electrons ejected per incident ion per square degree extrapolated from measurements of the restricted yield Y_R corresponding to the electron energy and angle windows of the apparatus (see below).

Of greater initial interest was our earlier finding² that the FWHM of convoy electron cusps measured when Si and O projectiles traverse solid targets (C, Al, Ag and Au) is independent of projectile nuclear charge, projectile charge state, velocity, and target over the velocity range ~ 6 -12 au, and is summarized by $\Gamma = 0.25 \pm 0.02$ au (for an analyzer having $\Delta E/E = 0.014$ and collecting electrons ejected into a cone of half angle $\Theta_0 = 1.8$ deg, centered on the forward direction).

Subsequent analysis of newer data by Breinig et al.¹³ shows that for Si, O, and C projectiles in the velocity range 7-12.5 au traversing He, Ne and Ar targets, the FWHM of ELC cusps is also $\Gamma = 0.26 \pm 0.04$ au, independent of q , v , and projectile Z , suggesting a close relationship between ELC and convoy electron production. This finding had been anticipated recently in a paper by Elston et al.¹⁴ concerning convoy electron production by channeled heavy ions in gold monocrystals, and much earlier still in one of the two first experiments^{15,16} concerning convoy electron production by channeled ions. Datz et al.¹⁵ interpreted their results for channeled 28 MeV oxygen and 20-30 MeV copper ions in $\langle 110 \rangle$ and random directions in gold monocrystals in terms of loss of bound electrons to the continuum.

However, Dettmann et al.,¹⁶ who studied convoy electron production by 200-300 keV protons in $\langle 111 \rangle$ and random directions in gold, interpreted their results instead in terms of charge transfer to the continuum (CEC in their parlance, ECC in ours) at or near the last atomic layer, citing capture from the 5d shell of gold as predominant under channeling conditions (vis-a-vis 5s, 5p, 5d for non-channelled ions). These findings are not necessarily inconsistent: It is known from experiments in gas targets⁵ that when barely bound electrons are available, ELC is dominant; but for bare nuclei (and presumably for ions whose velocity is such that the equilibrium charge $\bar{q} \approx Z$), ECC is dominant. The two experiments cited in Refs. 15 and 16 could be interpreted by invoking a blend of both mechanisms, with ELC strongly dominant in the former and ECC in the latter.

Until the work of our laboratory, contrasting ECC with ELC line shapes, it had not been realized how different the corresponding cusp shapes and widths actually were, nor how similar the cusp widths and symmetries were for ELC vis-a-vis convoy production by heavy ions.

Figures 1 and 2 provide graphic illustrations of the contrast. Figure 1 presents a plot of the number of electrons detected vs. electron velocity for 40 MeV O^{3+} ions traversing Ar under single collision conditions (solid line, spectrum dominated by ELC), overlaid with an analogous plot for ECC electrons produced by 40 MeV O^{8+} ions traversing Ar under otherwise identical conditions. Apart from low-energy Auger transitions arising from projectile excitation to multiply-excited Auger emitting levels appearing in the wings of the observed ELC cusp, it is seen that the ELC cusp is markedly narrower and more symmetric. No background has been removed from either spectrum.

Figure 2 provides an even more striking illustration of the dissimilarity of ECC vs. ELC cusps in shape. For O^{7+} projectiles on Ar a cusp obtained in

coincidence with O^{8+} (dotted line) is overlaid with a cusp containing all electrons not detected in coincidence with O^{8+} (solid line). This effectively resolves the ELC and ECC contributions. As the data set for both cusps is identical, the strong difference between ELC and ECC cusp shapes is directly demonstrated.

A typical convoy electron velocity spectrum is shown in Figure 3 for 16 MeV/u O^{9+} traversing a $30 \mu\text{g}/\text{cm}^2$ C foil target. For solid targets the velocity distribution is narrower than the ECC distribution and exhibits a skew toward the high velocity side. Apart from the skew, the convoy spectrum is very similar to ELC spectra acquired under very similar conditions and has identical width (within errors).

In proton impact work that has already been cited, as well as in more recently published work concerning convoy electron production by protons in carbon,¹⁷ the skew observed is similar to that for ECC in gases (though less pronounced), and opposite to the skew we see for heavy ions traversing not only C but also Ag, Al and Au polycrystalline solids. We indicate a plausible interpretation of this difference: If ECC is relatively important in the initial stage of convoy electron production, then ECC-type asymmetries are expected. If, however, ELC is the dominant mechanism, we expect symmetric ELC-type cusps, modified by a larger escape probability¹⁸ for $v_e > v$ electrons in our velocity range so as to produce the positive skew observed.

2. Coincidence experiments concerning convoy electron production by 1 to 8.5 MeV/u heavy ions traversing polycrystalline C, Al, and Au targets and $\langle 110 \rangle$ and $\langle 100 \rangle$ axial channels in Au

The electron spectrometric apparatus and experimental methods associated with our coincidence measurements have been described previously¹⁹ and need not be repeated here.

To aid in unraveling the puzzling array of similarities and differences among ECC, ELC, and convoy electron spectrum shapes and yields, we initiated coincidence experiments to investigate the dependence of shape and yield of the convoy electron spectrum on the charge q_e of the associated emergent ion, for ions traversing a gold monocrystal. For the best channeled ions, the fact that their charge often does not change throughout their entire crystal passage²⁰ makes such channeled ions useful probes.

A typical experimental result, taken from the paper of Laubert et al.,¹⁹ is shown in Figure 4, for 12 MeV $^{12}_{6}\text{C}^{2+}$ ions incident on a 40 $\mu\text{g}/\text{cm}^2$ Al target. A total, or singles, velocity spectrum is shown, together with the electron energy distribution observed in coincidence with the emergent C^{6+} ($\sim 25\%$ of the total), C^{4+} ($\sim 20\%$ of the total), and C^{3+} ($\sim 1.2\%$ of the total). The C^{5+} distribution accounted for 45% of the total and hence need not be shown. Lower final charge states were observed, but with intensities of less than 0.5% of the total; hence reliable electron velocity distributions (i.e., distributions having a trues to accidentals ratio greater than 5) could not be obtained.

Inspection of Figure 4 leads to the conclusion that no significant differences in the velocity distribution of the convoy electrons was observed as the final charge state of the projectile was changed. In fact, the FWHM (full width at half maximum) is nearly the same for all the final charge states of the projectile. Changing the incident energy of the projectile (from 12 MeV to 33 MeV carbon), the charge state of the projectile, the atomic number of the projectile (carbon, oxygen, and silicon (all at 1 MeV/u)) or the target material (aluminum, carbon and gold) did not alter this conclusion, i.e., the shape of the final convoy electron velocity distribution from solids is approximately independent of the final projectile charge state. The theoretical considerations of Day²¹ indicate a diffraction structure in the electron velocity distribution and a Z_1 dependence

of the FWHM of $\sim Z_1^{1/2}$. No diffraction structure is observed in Figure 4. However, the possibility that use of a higher resolution analyzer might reveal structure cannot be ruled out. The Z variation of the FWHM predicted by Day amounts to $\sim 20\%$ for the present ions and is within the experimental uncertainty.

The yield of convoy electrons per incident projectile can be obtained by an appropriate normalization and integration of the longitudinal velocity distribution shown in Figure 4. We found that the convoy electron yield, per projectile of charge state q_e , is independent of the final projectile charge state q_e . That is, the fraction of electrons coincident with a particular final charge state is just mirrored by the unweighted fraction of projectiles having that particular charge state. When the atomic number and energy of the incident projectile or the target material was changed, we found that the coincident convoy electron yield varied proportionately to the noncoincident (singles) convoy electron yield, and quantitatively agreed with the previous measurements of Laubert et al.²

The unanticipated observation of yield independence of emergent charge state argues against any "last layer" description of convoy electron origin in terms of binary electron capture or loss processes, at least at the very last layer, as these processes are well known to depend strongly on projectile ion charge state in the gas target case, and on projectile Z in the solid target case.

As noted above,²⁰ the charge of well-channeled ions often remains frozen throughout their entire crystal passage. In distinguishing Z and q dependences, this property makes such ions useful probes. In common with the results observed for polycrystalline targets, for $O^{6+,7+,8+}$ ions traversing the $\langle 110 \rangle$ and $\langle 100 \rangle$ axial channels in a Au monocrystal as well as a random direction, we have not detected any appreciable change in the shape of the convoy electron spectrum regardless of the choice of projectile Z, target Z_T , projectile velocity v, emergent charge q_e , or whether a channeling or random direction was chosen.

Concerning yields, using a Au monocrystal target ($\sim 300 \mu\text{g}/\text{cm}^2$) oriented in a random (non-channeling) direction, we found that the convoy yield per projectile ion is independent of emergent projectile charge state and simply mirrors the statistical fraction of the corresponding projectile charge state distribution just as in the polycrystalline target case. Since in both the ion-atom and the ion-solid collision case the yields scale rather strongly with Z , this observation is a surprise and again argues against a surface-layer origin for convoy electrons.

There is, however, a strong dependence of yield on emergent charge state q_e for well-channeled ions. For 2.4 MeV/u oxygen beams traversing the Au monocrystal, Table I displays the convoy electron yield $Y\langle ijk \rangle$ per emergent ion for a particular initial and final charge state.¹⁴ The measured fraction $[CF(q, q_e)]$ of emergent ions with this final charge state is also displayed in parentheses. $Y\langle ijk \rangle$ and $Y\langle \text{Rand} \rangle$ refer to particular channeling and random directions, respectively. It is evident from the table that convoy electron production for well-channeled ions is much suppressed, with the greatest suppression arising in the most open channel ($\langle 110 \rangle$) and for the most compact projectiles (0^{8+} , 0^{7+}).

Straightforward quantitative analysis yields some fascinating results. In a channel a large fraction, F_A , of ions is confined to collisions with Au conduction electrons ($5d^{10}$, $6s^1$), for which capture and loss cross sections are sharply reduced;²⁰ the remaining, smaller fraction, $F_B = 1 - F_A$, experiences collisions with more strongly bound electrons. We expect ions in group B to approach charge state equilibrium rapidly, and the corresponding convoy yield Y_B to be well approximated by $Y\langle \text{Rand} \rangle$.

For ions traversing the most open channel ($\langle 110 \rangle$) near channel center, where the low electron density suppresses both capture and loss and low electron momentum further suppresses capture, we expect the lowest convoy yields. Assuming

therefore that for group A ions the convoy yield Y_A (8^+ in, 6^+ out) is very small, we inferred the fractions $F_B(q_e)$ of class B ions that emerge with charge q_e from measured yields and charge fractions for each channel. Knowing the F_B 's, we calculated $Y_A(q, q_e)$ for all q and q_e for a consistency check and confirmed that all the Y_A 's are small compared to Y_B . The fraction of ions belonging to group B is given by $F_B = \sum_{q_e} F_B(q_e)$ and $F_A = 1 - F_B$. We find $F_A \approx 0.78$ for the $\langle 110 \rangle$ channel and ≈ 0.68 for the $\langle 100 \rangle$ channel. Using these F_A values and crystallographic values for the geometric area of each channel, the effective area available to group B ions and unavailable to group A ions is $1.3 \text{ \AA}^2$ out of $5.83 \text{ \AA}^2$ for $\langle 110 \rangle$, and also $1.3 \text{ \AA}^2$ out of $4.14 \text{ \AA}^2$ for $\langle 100 \rangle$. A unique value $r_{\text{CRIT}} = 0.65 \text{ \AA}$, corresponding to $\pi r_{\text{CRIT}}^2 = 1.3 \text{ \AA}^2$ can be deduced. Thus, only ions that have impact parameters $< 0.65 \text{ \AA}$ (group B) produce convoy electrons, with an efficiency approximating the random value. In Au atoms the 6s and 5d electrons have kinetic energies $\lesssim 10 \text{ eV}$. But the 5p and 4f electrons - which have binding energies of ~ 250 to 460 eV and are therefore far more efficient at contributing to capture according to the Bohr $v_e \sim v$ matching criterion - have mean radii ranging from 0.60 to $0.28 \text{ \AA}$. Therefore, the "magic" distance of $0.65 \text{ \AA}$ can be assigned a plausible physical interpretation.

A simple model which reproduces most of the observed values invokes the following features. Convoy production is initiated in close collisions throughout the bulk, while the final ion charge state is determined near the exit surface. A close relationship between ELC and convoy electron production is suggested by the fact that the widths of the convoy and ELC cusps are equal within uncertainty, and are similarly independent of projectile nuclear charge, projectile velocity, and target.¹ We suggest that convoy production is initiated by single or multiple electron capture events having $\sim 10^{-17} \text{ cm}^2$ cross sections,²² predominantly to excited states $\sim 90\%$ of the time,²³ followed immediately by ELC. Subsequent

electron scattering (elastic and inelastic) leads mainly to scattering into a wide range of angles, effectively extinguishing the convoy population. (Some unknown degree of repopulation is possible by secondary elastic scattering.) The net production of several convoy electrons per emergent ion is depleted by electron scattering to $\sim 10^{-3}$ to 10^{-2} observable electrons per ion.

The skew of the electron velocity distributions from solids toward electron velocities $v_e > v$ can be qualitatively and quantitatively explained by considering the velocity dependence, $\sim v_e^{1.6 \pm 0.1}$, of the mean free path of free electrons in bulk solids.¹⁸ We corrected the observed cusp shape by a velocity-dependent factor reflecting the exponential attenuation resulting from electron scattering within the bulk, as already displayed in Figure 3 for the typical case of 16 MeV O^{q+} traversing C. The resultant symmetric, peak-normalized curve is closely similar to experimental ELC cusps from C^{q+} , O^{q+} traversing Ne and Ar (apart from low-energy Auger lines which appear in the cusp wings.¹⁰ Since no fitting procedure beyond overall peak normalization is used, the ability to quantitatively symmetrize the skewed peak is viewed as support for the bulk production of convoys, a small fraction of which escapes through the surface.

A curious and unexplained enigma remains unresolved by our otherwise very successful model. Three facts need to be reconciled. The free electron scattering data suggest that all of the observed convoy electrons - though they are produced throughout the bulk - originate within the final ~ 20 Å of passage through the target (otherwise they scatter out). Yet the mean free path for projectile ion charge changing under our conditions is ~ 200 Å in C (perhaps an order of magnitude less in Au), so that any ion traversing the final 20 Å of target has little likelihood of changing charge. The fundamental question posed is: How can the correlation between emergent charge and convoy yield be broken in a distance of ~ 20 Å? Unless the correlation is broken, it is very difficult to

understand why the convoy yield is strongly dependent on projectile nuclear charge ($Z^{2.75}$), yet is independent of the emergent ionic charge (Z screened by 0 to 2 tightly bound K electrons).

Among the partially satisfactory solutions to this enigma, we have considered the following. It is possible that the issue of the final emergent charge state (at least for the projectiles that produce convoys) is not settled except in the last few atomic layers, or perhaps even downstream of the target (on an atomic scale). Arguments against this view include the following: First, for well-channeled ions a q^2 scaling of the energy loss is observed.²⁰ This scaling gives information about the charge of the ion before, during and after target passage. So, at least in the channeling case, the charge state of the ion as it passes the target can be tracked. The energy loss experiments were performed for the same projectile ions (O^{q+} , $q = 6, 7, 8$) at closely similar energies. Second, it is known from the work of Brandt et al.²⁴ that the target thickness dependences of Al K x-ray production cross sections by incident $O^{6+,7+,8+}$ traversing polycrystalline targets in a similar energy range are sensitive to q . A plausible interpretation of these data is that the x-ray production in the bulk is sensitive to the mean charge of the ion, which is a function of depth of penetration. The data can then be used to track the charge state distribution as the equilibrium charge-state distribution is approached. A third possibility is that the mean free paths for both electron elastic and inelastic scattering are larger for convoy electrons than for free electrons. Convoy electrons are expected to experience a powerful drag in the forward direction to the extent they remain near incompletely screened, highly charged projectile ions. A drawback to this argument is that these electron scattering mean free paths would need to be appreciably larger than the mean free paths for projectile charge changing in order to destroy the correlation. A fourth possibility is that the mean free

path for ion charge changing of $O^{6+,7+,8+}$ ions (at least for those ions that produce convoys) is far less than $\sim 200 \text{ \AA}$. One extreme form of this argument would invoke a nearly continuous change of the internal projectile ion charge state near the exit surface of the target. A fifth possibility is that the convoy electrons observed, originating within $\sim$ one mean free path for electron scattering, emerge from the same collision that settles the issue of the final emergent charge. For sufficiently close collisions (e.g., $0.65 \text{ \AA}$ for Au atoms), the convoy production rate might be expected to depend predominantly on Z rather than q . The additional assumption that the excitation, ionization, and charge transfer probabilities for each of several electrons participating in a multi-electron transition are statistically independent would conform to the observation that the probability of generating a convoy appears to be statistically independent of whether 0, 1, or 2 electrons are found bound to coincidentally observed O^{6+} , O^{7+} , and O^{8+} projectile ions. In this picture, observable convoy electrons (the many others formed scatter out) would be created in the same collision events that determine final ion charge, for the small fraction of such ions which undergo charge changing in the last few atomic layers. The expectation that such "last-minute" charge changing events are statistically rare, highly atypical collision events is in harmony with the small yield of observable convoy electrons. Such statistically rare, parasitic events are also expected to alter negligibly the characteristics of the overall charge state distribution of emergent ions, and indeed no such effects have been observed.

It is important to note that while the number of observable convoy electrons per ion is small ($\sim 10^{-3}$), the number of convoy electrons generated can easily reach several per ion. All that is required is for the target thickness to exceed several mean free paths for charge changing.

4. Capture and loss to Rydberg and super-Rydberg states in solids

As noted in a review article by Rudd and Macek,²⁵ projectile ionization (here ELC) can be thought of as the natural continuation of excitation to a sequence of orbits of ever-increasing principal quantum numbers into the continuum, provided an appropriate normalization of continuum states per unit bandwidth Δn relative to high n Rydberg states is chosen. Similarly, ECC may be regarded as a smooth extension of bound-state electron capture to high Rydberg states, lying just below the continuum, into the continuum.²⁵ Paraphrasing the elaboration of these ideas in a paper by Rødbro and Andersen²⁶ concerning ECC by protons in gases, we assume an average projectile or target excitation cross section $d\sigma_n/dE_n$ to be a slowly varying function of E_n because excitation cross sections to states with high principal quantum numbers scale approximately as n^{-3} , exactly compensating for a density of states varying as n^3 .

Following Ref. 26, we define a reduced cross section $\sigma_c = n^3 \sigma_n = n^3 \sum_{l,m} \sigma_{nlm}$, which is expected to be a slowly varying function of n . This scaling corresponds to the well-known n^{-3} scaling predicted by the Oppenheimer-Brinkman-Kramers (OBK) and Jackson-Schiff (JS) formulations of the first Born approximation to charge transfer.²⁷ Using L and P to denote laboratory and projectile frames, respectively, E_n to denote electron energy up to the ionization limit, and E_k that above it, continuation of the singly differential cross section above the ionization limit can be written:

$$(d\sigma/dE_n)|_P \simeq (\Delta E_n)^{-1} \sum_{E_n}^{E_n + \Delta E_n} (\sigma_{E_n})|_P = \Delta E_n^{-1} \sum_n^{n + \Delta n} \sigma_n \simeq (d\sigma/dE_k)|_P. \quad (1)$$

The Coulomb potential energy levels are $E_n = (-Z_E^2/2n^2)\text{Ry}$, so that ΔE_n may be expressed as $(Z_E^2/n^3)\Delta n \text{ Ry}$. If n^3 is assumed constant over a small range Δn ,

$$(d\sigma/dE_n)|_P \simeq \Delta E_n^{-1} \sum_n^{n + (n^3/Z_E^2 \text{ Ry}) \Delta E_n} \sigma_c/n^3 = \sigma_c/Z_E^2 \text{ Ry}. \quad (2)$$

Here Z_E is the effective nuclear charge seen by a Rydberg electron, presumably $Z_E \sim \bar{q}$. Using the continuity relation $(d\sigma/dE_k)|_P \simeq (d\sigma/dE_n)|_P = \sigma_c/Z_E^2 \text{ Ry}$, σ_c can be re-expressed in laboratory frame coordinates through the relation:

$$(d\sigma/dE_k)|_P = (d\sigma/dE_e)|_L \times (\Delta E_e/\Delta E_k), \quad (3)$$

where ΔE_e and ΔE_k are corresponding energy windows in the two reference frames. For our analyzer, $\Delta E_e = 0.014 E_e$, where E_e is the laboratory frame electron kinetic energy. Consideration of the kinematics (near zero deg) and of the apparatus resolution leads to $(\Delta E_e/\Delta E_k) = (16/0.014) = 1140$, so that a small energy window in the laboratory frame implies an extremely narrow band of energies in the projectile rest frame.

Accordingly, the laboratory frame escape cone (half-angle $\Theta_{\max}$) for electrons corresponding to the window ΔE_k is appreciably smaller than the acceptance cone (half-angle $\Theta_0 = 1.8$ deg) of the analyzer. A "filling factor" reduces the integration averaging over angles implied by

$$(d\sigma/dE_e)|_L \simeq \int_{\Delta\Omega_0} (d^2\sigma/dE_e d\Omega)|_L d\Omega \quad \text{to} \quad \int_{\Delta\Omega_{\max}} (d^2\sigma/dE_e d\Omega)|_L d\Omega. \quad (4)$$

The reduction factor R is not simply the ratio of the corresponding solid angles, because of the strong $1/k$ weighting of the doubly differential cross section arising from the Coulomb wave normalization factor²⁷ describing the cusp. Here k is the rest frame electron emission velocity. Accordingly, we write:

$$\sigma_c = (d\sigma/dE_e)|_L (\Delta E_e/\Delta E_k) (Z_E^2 \text{ Ry}) \times R, \quad (5)$$

where for our apparatus ($\Delta E/E = 0.014$, $\Theta_0 = 1.8$ deg), $R \simeq 0.059$, whereas for that of Rdbro and Andersen ($\Delta E/E = 0.01$, $\Theta_0 = 0.36$ deg), it is $R \simeq 0.23$. The value for R given by Rdbro and Andersen is 0.184, but this result appears to be low by $\sim 25\%$ owing to an integration error in computing the $(1/k)$ -weighted "disc-shaped" resolution volume corresponding to their energy and angle windows.

Another adjustment, of inadequately known magnitude, is needed to account for the assumption of Rødbro and Andersen - an assumption also of the ECC theory of Dettmann, Harrison and Lucas,⁷ unjustified in retrospect - that the low-energy electrons are isotropically distributed in the projectile rest frame. It is evident from the work of Breinig et al.²⁸ as well as that of Meckbach et al.²⁹ and Macek et al.³⁰ that ECC cusps display forward-backward asymmetries characterized by finite $p, d \dots$ partial waves in the scattering amplitude. The step observed by Breinig et al.²⁸ is a clear manifestation of the relative importance of at least one partial wave amplitude whose angular dependence contains an odd Legendre polynomial (like a p-wave).

Lacking the detailed experimental information concerning the velocity distribution in the projectile rest frame, which may be extracted from future millidifferential angular distribution measurements near the forward direction, we will assume approximate isotropy in our subsequent discussion. However, the estimates of σ_c we give, while informative, can have only qualitative significance because of the unknown adequacy of the isotropy assumption.

In discussing σ_c values derived from our experiments for the case of solid targets, we will focus our attention on C target as prototypical. Eq. (5) has been used to generate values of σ_c . Corresponding values of $(d\sigma/dE_e)|_L$ are obtained by first multiplying the values of $(d\sigma/d\Omega)|_L$ shown by our experimental $\Delta\Omega$ of 3.1×10^{-3} sr. Then we use the following equation, adapted from the work of Dettmann, Harrison and Lucas,⁷ to generate a normalized value for $\frac{d\sigma(\theta_0)}{dv_e}$ at $v_e = v$ by finding the value of the normalization constant required to make this quantity correspond to the experimentally observed yield:

$$\frac{d\sigma(\theta_0)}{dv_e} \approx \text{constant} \times \{[(v_e - v)^2 + (v\theta_0)^2]^{\frac{1}{2}} - |v_e - v|\}. \quad (6)$$

Finally, we transform $(d\sigma/dv)|_L$ to $(d\sigma/dE_e)|_p$ by elementary kinematics.

Because the analysis of data pertaining to O^{q+} beams traversing carbon targets can easily be extended to other projectile-target combinations through use of the yield curves estimated by Laubert et al.,¹ we give here only results for O^{q+} ions in C over the range 1 to 4 MeV/u. In using these curves, it is important to note that they provide estimates of total yields Y in units of electrons per projectile particle, integrated over all electron energies and angles, extrapolated from the actual restricted yield measurements Y_R . These restricted yield measurements sampled these quantities over a restricted regime (typically 1 au of velocity and $\Theta_0 = 1.8$ deg). To avoid major uncertainties in the extrapolation to Y , we deal here only with the quantity $Y_R \equiv Y[1 - (1 + Cv) \exp(-Cv)]$, where $C = 0.0538 \Theta_0$ (Θ_0 in deg) and the projectile velocity v is given in au. The quantity Y is adequately estimated from $Y = 1 \times 10^{-4} C(Z_T) Z^m E^{-n}$, where Z is the atomic number of the incident particle of energy E in MeV/u, $m = 2.75 \pm 0.02$, $n = 2.25 \pm 0.1$, and $C(Z_T)$ is a target-dependent parameter ($C(C) = C(Al) = 1.0$, $C(Ag) = 1.25$, and $C(Au) = 1.65$).

Though, as noted earlier, convoy electron production is thought to be a bulk effect, it is thought that typically one observes only those which originate in the last few atomic layers because the remainder scatter out of the forward direction before escape. For convenience in generating effective values of σ_c for the solid target case to compare with the gaseous target case, we therefore re-express the yield result in terms of a cross section per target atom by dividing by the surface density of the target (in effect, making a "last layer approximation" not to be taken literally). The target material-dependent cross section σ corresponding to Y thus becomes $\sigma = 5 \times 10^4 C'(Z_T) Z^{2.75} E^{-2.25}$ b/atom, where $C'(C) = 1.0$, $C'(Al) = 1.3$, $C'(Ag) = 1.7$, and $C'(Au) = 2.2$. The actual measured yields Y_R correspond to the restricted cross section σ_R , where $\sigma_R \equiv \sigma[1 - (1 + Cv) \exp(-Cv)]$.

The specific results of this analysis for O^{9+} ions traversing carbon targets are displayed in Table II. If one makes the plausible assumption that $\sigma_c = n^3 \sigma_n$ is adequate for $n \gtrsim 4$ (in parallel with our gas target data), then approximate predictions of σ_n for oxygen, hydrogen, or other atoms emergent from C foils can be generated. Table III lists such estimates. Comparison of the data for σ_c for O^{8+} on He with data for O^{9+} on thin carbon targets shows that effective convoy electron production rates in solids exceed those for He by about three orders of magnitude (and by about one to two orders of magnitude for Ne and Ar targets). This high convoy production rate can be used to derive predicted yields of Rydberg and high Rydberg states through the same scaling $\sigma_c = n^3 \sigma_n$ as is thought to apply for gases in the OBK approximation if once again continuity across the ionization limit is invoked. For O^{9+} and proton beams at 1 MeV/u, the band $\Delta n = 4-10$ accounts for a cross section of ~ 440 Mb and ~ 23 kb respectively; the band $n = 10-20$ for ~ 47 Mb and ~ 24 kb respectively; $n = 20-50$ for ~ 13 Mb and ~ 0.7 kb; $n = 50-100$ for ~ 1.9 Mb and ~ 96 b; and $n = 100-\infty$ for ~ 0.6 Mb and ~ 32 b. (For $n \geq 10$, the approximation $\sum_n^{n+\Delta n} \sigma_n = \sigma_c \int_n^{n+\Delta n} \frac{dx}{x^3} = (\sigma_c/2) [1/n^2 - 1/(n + \Delta n)^2]$ has been used.) Very similar estimates are easy to generate for other Z, v values in other targets using the $Z^{2.75}, E^{-2.25}$ scalings of the expressions for σ_R and σ given above.

A very well known, systematic problem affecting lifetime measurements using the beam-foil technique³¹ is associated with estimating the amount of cascade feeding of lower levels repopulated from higher levels as a function of time. Initial population estimates enter at the starting point of such calculations. The degree of success of application of the population estimates just provided remains to be worked out. For this purpose, it is important to specify σ_{nl} , not just σ_n . The degree of dominance of s-state production for arbitrary Z, v is not known to the authors. However, for high n levels, both stray fields and those associated with analysis of ECC, ELC electron spectra using the present experimental

techniques are sufficient to create statistical mixtures of ℓ states through Stark mixing, and in the case of high n levels, to cause appreciable field ionization. Since the weight of evidence is that n -state populations continue smoothly through the ionization limit, and that $\sigma_c = n^3 \sigma_n$ is a useful estimate both above and below the ionization limit, it would appear that the question of whether a particular high Rydberg state is slightly bound or slightly unbound is only of minor importance in interpreting ECC, ELC, and convoy spectrum shapes and yields.

Acknowledgements

A number of colleagues cited in the references to the work of our laboratory have contributed greatly to the carrying out of the experiments described, aided by generous help from staff at Oak Ridge National Laboratory, Lawrence Berkeley Laboratory, and Brookhaven National Laboratory. Substantial contributions have also been made by other Oak Ridge National Laboratory colleagues Gerald Alton and M. O. Krause. Finally, we would like to acknowledge the energetic participation of our late colleague, Roman Laubert. This is the final work we were able to carry out in collaboration with him before his death; we will sorely miss him.

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TABLE I

Convoy electron yield (%) per emergent ion, for O^{8+} incident at 2.4 MeV/u on Au in the $\langle 110 \rangle$, $\langle 100 \rangle$, and random directions. The yield is normalized to the measured random yield of $\sim 3.8 \times 10^{-4}$ electrons/ion. The number in parentheses is the fraction (%) of emergent ions in state q_e .

q in	q _e out	8+		7+		6+	
8+	Y<110>	21	(68)	39	(28)	82	(4)
	Y<100>	37	(59)	58	(35)	79	(6)
	Y<Rand>	100	(26)	100	(59)	100	(15)
7+	Y<110>	29	(42)	24	(51)	58	(7)
	Y<100>	37	(52)	47	(42)	71	(6)
	Y<Rand>	100	(25)	100	(60)	100	(15)
6+	Y<110>	37	(31)	29	(42)	21	(27)
	Y<100>	39	(49)	45	(42)	47	(9)
	Y<Rand>	100	(27)	100	(57)	100	(16)

Table II. Values of Y_R , σ_R , and $(Z/Z_E)^2 \sigma_C$ for oxygen ions and protons traversing amorphous carbon targets. Values for σ_C can be estimated by multiplying column 3 entries by $(Z_E/Z)^2$, where Z_E is an assumed effective charge for convoy production.

E (MeV/u)	Y_R (oxygen) in units of 10^{-3} per pro- jectile/deg ²	σ_R (oxygen) in units of 10^{-18} cm ² /deg ²	$(Z/Z_E)^2 \times$ σ_C (oxygen) in units of 10^{-15} cm ²	Y_R (protons) in units of 10^{-6} per pro- jectile/deg ²	σ_R (protons) in units of 10^{-21} cm ² /deg ²	σ_C (protons) in units of 10^{-19} cm ²
1	3.8	1.9	12.6	13	6.3	6.4
1.5	2.1	1.1	5.8	7.0	3.5	2.9
1.8	1.6	.81	3.9	5.3	2.6	2.0
2.5	.98	.49	2.0	3.2	1.6	1.0
3.2	.67	.33	1.2	2.2	1.1	.65
3.8	.51	.25	.84	1.7	0.83	.45

Table III. Estimated cross sections $\times (Z/Z_E)^2$ for Rydberg state production from O^{9+} , H^+ ions incident on C foils at 1 MeV/u. Cross sections for a chosen effective charge Z_E can be obtained by multiplying the entries by $(Z_E/Z)^2$.

n	O^{9+} incident units of Mb	H^+ incident units of barns
4	196	10,000
5	101	5,120
6	58	2,963
7	37	1,866
8	25	1,250
9	17	878
10	13	640
20	1.6	80
30	.47	24
40	.20	10
50	.10	5.1
60	.058	3.0
70	.037	1.9
80	.025	1.3
90	.017	.88
100	.013	.64

Figure Captions

Figure 1. Velocity spectrum of electrons emitted in the forward direction in collisions of 40 MeV O^{3+} ions with Ar (solid line). The spectrum shows a typical ELC cusp, with low-energy projectile rest frame Auger structure superposed. A representative peak-normalized ECC spectrum (dots) for 40 MeV O^{8+} ions traversing Ar is superposed.

Figure 2. Cusp for 20 MeV O^{7+} projectiles on Ar obtained in coincidence with O^{8+} (dotted line), overlaid with cusp containing all electrons not detected in coincidence with O^{8+} (solid line). The former is an ELC spectrum while the latter represents an ECC spectrum. Differences in ELC and ECC cusp shapes are obvious.

Figure 3. Spectrum of convoy electrons emergent near 0 deg from 16 MeV O^{9+} ions traversing a 30 $\mu\text{g}/\text{cm}^2$ C foil. The upper data points are obtained from the raw spectrum (lower points), through a correction factor $v_e^{-1.6}$, to account for the electron escape depth velocity dependence estimated from Ref. 18. The lower curves represent respective fitted cusp shapes, which better display the degree of symmetrization produced.

Figure 4. The longitudinal velocity distribution of convoy electrons emerging from solids when 12 MeV $^{12}_6\text{C}^{2+}$ is incident on 40 $\mu\text{g}/\text{cm}^2$ Al targets. The "singles" or noncoincident distribution is shown in the lower left-hand corner. The electron velocity distributions in coincidence with the final charge states of C^{6+} , C^{4+} , and C^{3+} are shown in clockwise arrangement starting in the upper left-hand corner. The vertical scale (intensity) is arbitrarily normalized for each spectrum.

INTENSITY

VELOCITY (A.U.)