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Target-thickness dependence of the convoy-electron yield measured in coincidence with exit charge states in fast-ion–solid collisions

Y. Yamazaki,* H.-P. Hülskötter, M. Breinig, R. DeSerio, J. Burgdörfer, T. Underwood, J. Gibbons, and I. A. Sellin
University of Tennessee, Knoxville, Tennessee 37996
and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

P. Pepmiller
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

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We have measured the yield of convoy electrons produced by 2-MeV/u C projectiles incident on C foils as a function of target thickness (0.8–50 $\mu g/cm^2$) for incident charge states $q_i = 4-6$ and exit charge states $q_e = 4-6$. Normalizing the yields measured in coincidence with ions of exit charge state q_e to the total number of projectiles exiting with charge state $q_e - 1$ we conclude that the target-thickness dependences found support the model of electron loss to the continuum as the dominant convoy-electron production mechanism even for bare projectiles incident on the thinnest targets. For equilibrium-thickness foils the electrons are lost predominantly from excited states.

Fast heavy ions passing through thin solid targets often exit accompanied by convoy electrons moving with a velocity $\mathbf{v}_e$ very close to the ion velocity $\mathbf{v}$. In the laboratory frame the velocity spectrum of convoy electrons emerging into a forward cone with half angle θ_0 typically between 1 and a few degrees is a cusp-shaped peak centered at v, and the cross section $d\sigma/dv\,d\Omega$ for the emission of convoy electrons at zero degree is nearly symmetric about the beam velocity v. Several mechanisms for the production of convoy electrons have been proposed, such as projectile-electron loss to low-lying continuum (ELC) states,[1] target electron capture into the same low-lying continuum state of the projectile (ECC),[2] wake-riding electron release into the projectile continuum,[3] and free-electron transfer to the projectile continuum (FETC).[4]

In heavy-ion–solid collisions recent experiments favor the ELC process as the dominant production mechanism. Shapes and widths of convoy-electron velocity spectra are similar to those of electrons lost by projectiles in ion-gas collisions under single-collision conditions.[5] Doubly differential measurements, differential in convoy-electron velocity and laboratory-ejection angle, reveal an anisotropic electron distribution highly transverse to the beam direction in the projectile frame.[6] The transverse character of this distribution is a characteristic of the ELC process, but its high multipole content is not expected for ELC from inner shells.[7] The range of experiments measuring the yield of convoy electrons as a function of the exit charge state of the accompanying ion has recently been extended to higher-Z projectiles and lower projectile energies.[8] Dividing the number of convoy electrons detected in coincidence with an ion of exit charge state q_e by the number of ions emerging from the target with charge state $q_e - 1$, Hülskötter *et al.*[8] found that the convoy electron yield $Y_c(q_e, q_e - 1)$ so normalized had a charge-state dependence on $q_e - 1$ similar to the dependence of the total-electron-loss cross section in ion-atom collisions. They were therefore able to interpret the observed q_e dependences in terms of primary electron-loss events in the target.

In the above-mentioned experiments, equilibrium thickness targets were used. In equilibrium thickness targets the exit charge state distribution is independent of the incident charge state of the projectile q_i; the memory of q_i is erased by subsequent capture and loss processes in the target. In the present work nonequilibrium targets were used. The experiment was designed to investigate if *even for bare projectiles incident on the thinnest targets* the dominant convoy-electron production mechanism is the electron loss to the continuum process or if the target electron capture to the continuum process contributes significantly under those conditions.

In the present work we report on measurements of the convoy-electron yield, measured in coincidence with the emergent charge state of the projectile, as a function of the target thickness for a range of incident projectile charge states. In our experiments 2-MeV/u C beams with incident charge states $q_i = 4-6$ were passed through 0.8 $\mu g/cm^2$ to 50-$\mu g/cm^2$ C foils.[9] The convoy-electron yield was measured in coincidence with exit charge states $q_e = 4-6$ for all q_i. Projectile species and energy were chosen such that the measured exit charge states are not seriously affected by projectile autoionization events after the foil, i.e., the Betz-Grodzins process[10] is not important in the present collision system. The beam diameter on target was less than 0.5 mm and the angular spread of the incident beam was approximately 0.01°. Emergent ions of charge state q_e were separated using an electrostatic parallel plate charge state analyzer and detected by a channel electron multiplier. Convoy electrons were energy analyzed using a 160° spherical sector electrostatic analyzer with energy resolution $\Delta E/E = 0.015$ accepting electrons emitted into a cone of half angle $\theta_0 \cong 2°$ about the beam direction. Target foils of different thicknesses were positioned in the entrance focus of the spherical sector analyzer mounted on 75-μm-thick brass plates with small 1.6-mm×4.7-mm eliptical holes.

Coincidences between convoy electrons and ions of charge state q_e were established by requiring that the time difference between the arrivals of the electron and the ion at their respective detectors fell into a 15-ns-wide window, set using a time-to-amplitude converter (TAC). During the experiment the number of electrons detected in coincidence with ions of charge state q_e was normalized to the total number of ions exiting with charge state q_e. The ratio of true coincidences to random coincidences in our experiments was ~100:1.

The shape of the measured cusp-shaped convoy-electron velocity distribution was independent of the target thickness, the incident projectile charge state q_i, and the exit charge state q_e. This was shown by measuring the convoy-electron yield in coincidence with the emergent ion charge state q_e for convoy electrons with different laboratory frame velocities, corresponding to the top of the cusp ($V_e = v$) and to the points with $\sim\frac{1}{2}$ and $\frac{1}{4}$ maximum count rate. Accordingly, in this paper we only present the convoy-electron yield Y_c for convoy electrons with velocity $V_e = v \pm \Delta v$ where Δv is determined by the acceptance of our analyzer.

Figure 1 displays the convoy yield $Y_c(q_e)$ measured in coincidence with ions of exit charge q_e normalized to the total number of ions $N(q_e)$ of that charge state, for C^{4+} [1(a)], C^{5+} [1(b)], and C^{6+} [1(c)] ions incident on C foils as a function of foil thickness. Figure 2 shows the exit charge state distribution $F(q_e)$ as a function of target thickness for all incident charge states. Charge state equilibrium is reached for foils thicker than ~10 $\mu g/cm^2$. The average charge state of the emergent ion is $\bar{q}_e = 5.6$ after passage through equilibrium thickness targets. It is interesting to note that in Fig. 1 for nonequilibrium thickness foils the yield $Y_c(q_e)$ is larger than the yield for equilibrium thickness foils if $q_e > q_i$, and smaller for $q_e < q_i$ irrespective of the incoming charge state q_i. For equilibrium thickness foils $Y_c(q_e)$ is not completely independent of q_e.

Normalizing the convoy yield $Y_c(q_e)$ to $N(q_e)$ (Fig. 1) is appropriate if ECC or wake-riding release processes produce most convoy electrons. However, if single electron loss to the continuum near the exit surface of the target is the dominant convoy-electron production mechanism then the number of electrons emerging with an ion of charge state q_e is expected to be proportional to the number of ions exiting with charge $q_e - 1$, provided that charge-changing collisions after convoy production are relatively unlikely.[8] The renormalized convoy yield $Y_c(q_e, q_e - 1)$, i.e., the number of electrons accompanying an ion of charge q_e divided by the total number of ions of charge $q_e - 1$, is proportional to the effective electron loss to the continuum cross section $\sigma_{q_e-1}^{\mathrm{ELC}}$ for ions of charge state $q_e - 1$, irrespective of foil thickness,

$$Y_c(q_e, q_e - 1) \equiv \frac{F(q_e)}{F(q_e - 1)} Y_c(q_e) \propto \sigma_{q_e-1}^{\mathrm{ELC}} . \quad (1)$$

The effective electron-loss cross section, however, depends on the fraction of projectile ions in excited states since electron loss is more probable from excited states than from the ground state.[11]

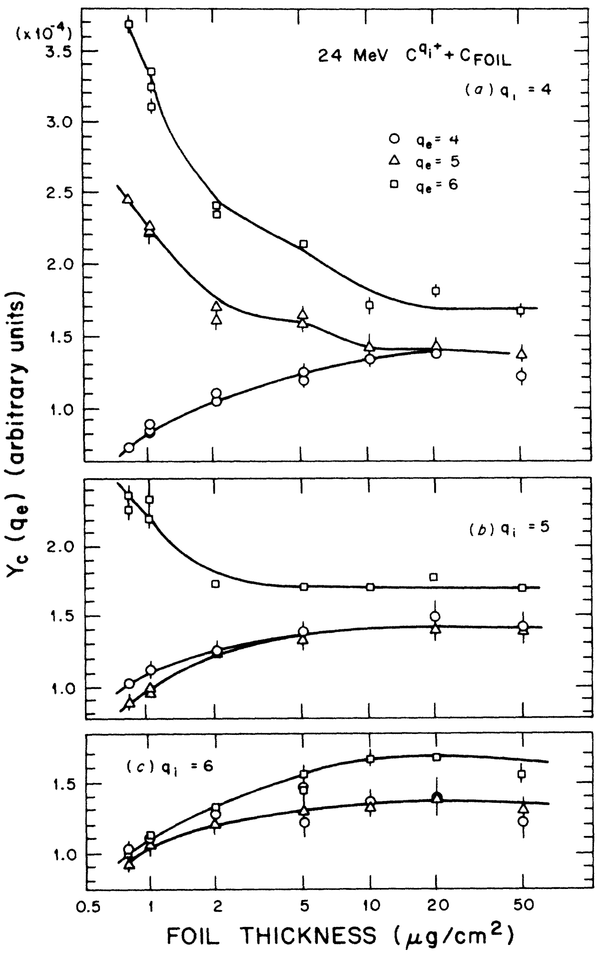

FIG. 1. Convoy-electron yield $Y_c(q_e)$ measured in coincidence with ions of exit charge q_e normalized to the total number of ions $N(q_e)$ of that charge state as a function of foil thickness for 2-MeV/u C^{q_i+} ions on C foils.

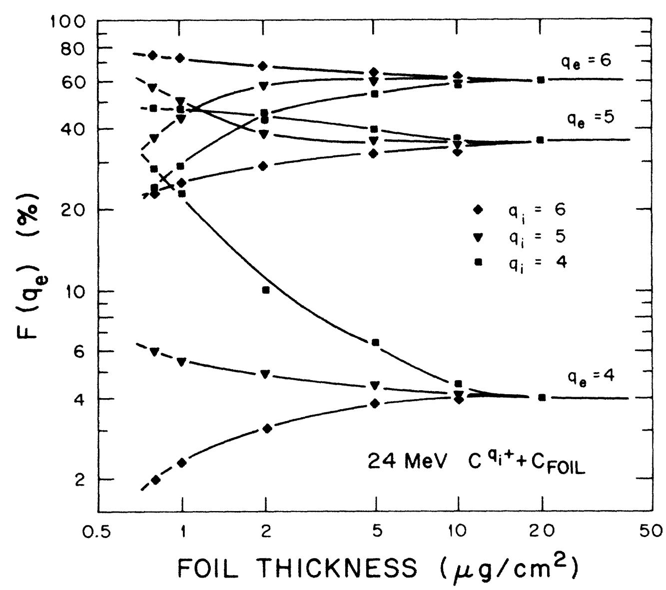

FIG. 2. Exit charge-state distribution $F(q_e)$ as a function of foil thickness for 2 MeV/u C^{q_i+} ions on C foils.

Figure 3 displays the renormalized convoy yield $Y_e(q_e,q_e-1)$ for all incident charge states and for exit charge states $q_e=5$ and $q_e=6$ as a function of target thickness. Most significantly, we find that the yield $Y_c(q_e,q_e-1)$ for $q_i=6$, $q_e=6$, and for $q_i=6$, $q_e=5$ is nearly independent of foil thickness. This is the signature of the electron loss to the continuum process. For the ELC process to be the dominant convoy-electron production mechanism in the case $q_i=6$, $q_e=6$ the bare incoming ion must first capture an electron into a bound state. Such capture preferentially populates excited states. The captured electron is lost as the ion exits the foil. The measured yield $Y_c(q_e,q_e-1)$ is proportional to the electron-loss cross section from moderately excited states for all foil thicknesses and therefore is independent of target thickness. In Fig. 3(a) the yield $Y_c(q_e,q_e-1)$ for $q_i=6$, $q_e=5$ is displayed. For ELC to be the dominant convoy-electron production mechanism this combination of incoming and emerging charge states requires that the bare projectile captures two electrons, one of which is lost into a low-lying continuum state. $Y_c(q_e,q_e-1)$ is then again proportional to the electron-loss cross section from excited states, independent of foil thickness as measured. The small increase in the yield for the thinnest foils supports a picture in which the charge state fraction $F(q_e=4)$ still appreciably increases over the distance in the foil over which a convoy electron can escape from the foil. This distance has been shown to be appreciably larger for convoy electrons accompanying high-q ions than for free electrons of the same speed,[12] and we observe a rapid increase of $F(q_e=4)$ with target thickness for the thinnest targets (Fig. 2).

We conclude that even for bare ions incident on the thinnest foils our measured thickness dependences carry the signature of the ELC process. In addition, even in this extreme case the shape of the convoy-electron cusp does not exhibit the skewness toward lower velocities characteristic of the electron loss to the continuum cusps.[1] We therefore conclude that even for bare projectiles and very thin targets the ECC process does not contribute significantly to the measured yield.

The renormalized yield $Y(q_e,q_e-1)$ for $q_i=4$, 5 and $q_e>q_i$ increases with target thickness for foil thicknesses 0.8 μg/cm to 10 μg/cm^2. We can qualitatively interpret this observed thickness dependence in terms of the dependence of the effective ELC cross section on the fraction of projectile ions exiting the foil in excited states. For example, the $q_i=5$ projectile ions enter the foil with one electron in the ground state. For very thin foils the fraction of C^{5+} ions exiting the foil in excited states is small and convoy electrons produced by C^{5+} ions are lost from the ground state. As the foil thickness increases the fraction of C^{5+} ions in excited states increases as a consequence of multiple collision in the foil, and the effective ELC cross section increases with foil thickness until equilibrium thickness is reached. We similarly explain the increase in $Y(q_e,q_e-1)$ for $q_i=4$, $q_e=5$ projectile ions. The fraction $F(q_e=4)$ rapidly decreases with foil thickness until equilibrium is reached (Fig. 2). As equilibrium is approached more charge-state-4 ions are partially produced from charge-state-5 ions by electron capture into excited states, which explains the increase in the effective ELC cross section.

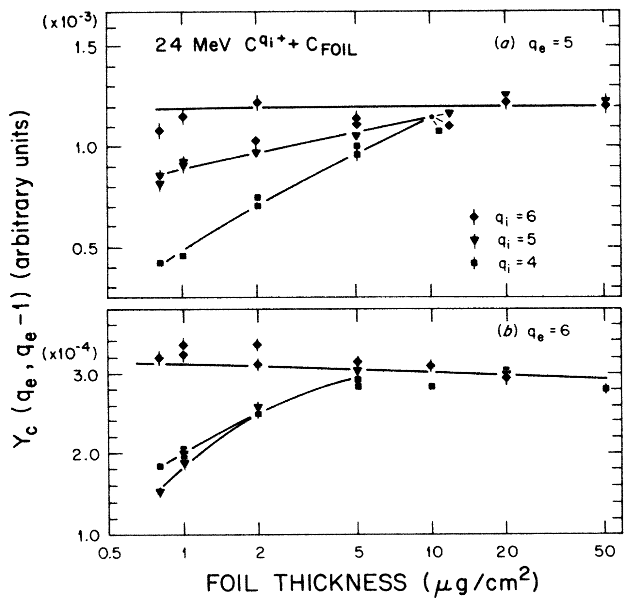

FIG. 3. Renormalized convoy-electron yield $Y_c(q_e,q_e-1)$ measured in coincidence with ions of exit charge q_e normalized to the total number of ions $N(q_e-1)$ of charge state q_e-1 as a function of foil thickness for 2 MeV/u C^{q_i+} ions on C foils.

As shown in Fig. 3(a) the thickness dependence of $Y_c(q_e,q_e-1)$ for $q_i=5$, $q=5$ is not strong but distinct. This dependence cannot simply be explained by an increase of the fraction of charge-state-4 ions in excited states but is probably due to a decrease in the charge state fraction $F(q_e=5)$ over distances from which convoy electrons escape from the foil for nonequilibrium thickness foils. Such a decrease will lower the measured coincidence yield $Y(q_e)$ and therefore also the renormalized yield $Y(q_e,q_e-1)$.

The experimental results presented in this paper strongly support the view that the primary production mechanisms for convoy electrons is projectile electron loss to low-lying continuum states for all target thicknesses and for all incoming and emerging charge states. In addition the data infer that for equilibrium thickness targets moderately excited states contribute significantly to the ELC process.

To gain more detailed information about the excited state distribution inside the foil further experiments should include measurements of the multipole content of convoy-electron velocity distribution in the projectile frame.[3]

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*On leave from Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Tokyo, Japan.
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