Exit charge state dependence of convoy electron production
in heavy-ion solid collisions

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Abstract

The dependence of the yield of convoy electrons emitted near the forward direction in collisions involving fast ions and thin solid targets on the emergent projectile charge state is presented and described in terms of primary electron loss events in the solid. The data include a large array of projectiles, projectile energies and charge states, as well as targets ranging in thickness from the non-equilibrium well into the equilibrium thickness region. The description presented is consistent with other experimental and theoretical results indicating that the convoy electron production is closely linked to the ELC process observed in binary ion-atom collisions, with the dominant contribution to the convoy yield stemming from excited states of the projectile.

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1. Introduction

The production of free electrons ejected in ion-solid collisions with electron velocities $\vec{v}_e$ close to the emergent projectile velocity $\vec{v}_p$ has been studied in many laboratories [1-6]. These so-called convoy electrons populate low-lying continuum states of the projectile. Their velocity spectrum recorded for emission into a forward cone with half angle θ_0 (typically between one and a few degrees and centered about the forward direction) shows a cusp-shaped peak centered at v_p . In ion atom collisions cusp-shaped distributions are observed for both binary electron-capture-to-continuum (ECC) and electron-loss-to-continuum (ELC) events. ECC cusps for heavy ions are strongly skewed towards lower velocities and have full width half maxima which are roughly proportional to v_p [3]. When loosely bound projectile electrons are available ELC cusps are observed which are instead nearly symmetric with widths which are almost independent of v_p [7,8]. Convoy electron cusps produced in heavy-ion solid collisions at MeV/u energies exhibit approximately velocity independent widths as well [3,7]. The cusp shapes are very similar to those observed for ELC cusps as can be seen in Fig. 1 which displays typical velocity distributions for ECC, ELC and convoy electrons.

Several mechanisms for the production of convoy electrons in ion-solid collisions have been proposed, some of which are ECC [2], ELC [3], capture to a high- n state quickly followed by ELC with near unity probability [3], and the ejection of wake-riding electrons into the projectile continuum [9]. Recent experiments strongly support the

close kinship between convoy electron production and binary ELC, which is indicated by the similarity in shape (Fig. 1). In a detailed measurement of doubly differential angular distributions Berry et al. [10] found an anisotropic electron distribution which is highly aligned transverse to the beam axis. Such a distribution is characteristic for the ELC process, however, the high multipole content observed can not be found for ELC from inner shells [11]. The conclusion that ELC contributions from excited states dominate the production of convoy electrons finds support in experiments by Betz et al. [12] who measured the population of high Rydberg states produced in fast ion-solid collisions and who conclude that a considerable fraction of the beam is in excited states while passing through the foil. They infer that the excitation to high Rydberg states, closely linked to the excitation to low lying continuum states, is a bulk effect.

An ion passing through a thin amorphous target (e.g. a C foil) undergoes charge changing collisions, i.e. capture of target electrons into or loss of projectile electrons from bound states. A characteristic parameter for charge changing collisions is the mean free path (MFP) λ_{cc} which is largely determined by the charge changing cross sections for deeply bound states. λ_{cc} is roughly of the order of the equilibrium thickness necessary to completely erase the memory on the initial charge state q_1 through subsequent capture and loss processes. Convoy electrons detected in the experiment are electrons excited to low-lying continuum states of the projectile in a thick "last layer" of the foil whose thickness is determined by the mean free path of convoy electrons λ_c . Experiments by Sellin et al. [13] and

Schramm et al. [14] found that λ_c for electrons accompanying high- q ions is enhanced relative to the MFP for free electrons traveling with the same velocity. The latter is determined by both elastic scattering (angular straggling) and inelastic scattering (energy loss) with target atoms. For highly charged projectile ions the enhanced MFP could be due to Coulomb focussing redirecting the electron velocity along the forward direction when secondary convoy electron scattering events occur [15,16]. For low q ions (e.g., protons), no such enhancement has been observed.

In this paper we will present a discussion unifying two recent experiments performed in this laboratory in which the yield of convoy electrons has been measured in coincidence with emergent projectile charge states for various projectiles, projectile energies, and target foil thicknesses. The main purpose of these experiments was to investigate the conjecture of the dominance of ELC in the production of convoy electrons.

2. Data Analysis

The first experiment investigated the dependence of the convoy yield $Y(q_e)$ on the emergent projectile charge states q_e for 0.5 and 1.5 MeV/u O^{q_1+} and 0.5 and 1.0 MeV/u Si^{q_1+} and Cl^{q_1+} projectiles incident on 15 and 30 $\mu\text{g}/\text{cm}^2$ C foils [17]. The convoy yield has been determined by integrating the measured cusps over a fixed velocity intervals (FWHM). The foils used were of equilibrium thickness. In a second experiment 2 MeV/u C^{q_1+} ions ($q_1=4-6$) were sent through 0.8 to 50 $\mu\text{g}/\text{cm}^2$ C foils [18] (equilibrium thickness $\approx 10 \mu\text{g}/\text{cm}^2$) [19]. The

convoy yield, measured at the top of the cusp, was determined in coincidence with emergent charge states ($q_e=4-6$) for all incident charge states. A detailed description of the experimental set-up can be found in references 17 and 19.

Our discussion starts with the rate equation for the convoy yield

$$dY(q_i, q_e, x)/dx = R(q_i, q_e, x) - Y(q_i, q_e, x)/\lambda_c, \quad (1)$$

with $R(q_i, q_e, x)$ the source term, which is a function of the number of electrons in (excited) projectile states and the respective ELC cross sections. We have displayed only the experimentally controlled variables q_i , q_e , and x of R and Y even though they depend also on the mean charge state $\bar{q}$ and the nuclear charge Z_p . Eq. (1) has the non-stationary solution

$$Y(q_i, q_e, x) = \int_0^x dx' R(q_i, q_e, x') \exp\{-(x-x')/\lambda_c\}, \quad (2)$$

where $x=0$ defines the entrance surface of the foil and x is the path length. For equilibrium thickness foils the source term $R(q_i, q_e, x)$ becomes independent of q_i and x since the distribution of charge states as well as the distribution of excited states are in equilibrium, i.e. $R(q_i, q_e, x) \rightarrow R(q_e)$. Eq. (1) then has the stationary solution

$$Y(q_e) = \lambda_c R(q_e). \quad (3)$$

In the following we will first discuss the equilibrium thickness data,

based on Eq. (3), followed by a discussion of the inherently more complex non-equilibrium thickness data, based on Eq. (2).

Acknowledging previous experimental evidence that ELC in the bulk is the dominant mechanism in the production of convoy electrons [12-14] the source term in Eq. (3) is to first order proportional to the number of ions detected per unit of time in charge state (q_e-1) , $N(q_e-1)$, times the ELC cross section, $\bar{\sigma}_{ELC}$, weighted over the excited state distribution. Eq. (3) becomes

$$Y(q_e) = \lambda_C n_T N(q_e-1) \bar{\sigma}_{ELC}, \quad (4)$$

with n_T the number density of target atoms. Multiple charge changing processes have been neglected since their cross sections are typically smaller by a factor ≥ 3 [3] relative to single capture or loss cross sections. Projectiles and projectile energies were chosen such that the measured exit charge states in few-electron systems are not seriously affected by autoionization events after the foil. The q_e -dependence of the above equation is mostly contained in $\bar{\sigma}_{ELC}$, since the q_e -dependence of λ_C is expected to be rather weak based on recent experimental data [13,14]. For the high- q , high- v_p projectiles and equilibrium thickness targets under consideration the MFP for charge changing collisions, λ_{CC} , is larger than λ_C , the escape depth for convoy electrons [17]. Therefore charge changing collisions subsequent to the production of a convoy electron become relatively unlikely and $N(q_e-1)$ can be assumed to be approximately constant over a distance $\sim \lambda_C$.

While previous similar coincidence measurements [3,5,6] show

largely varying q_e -dependences due to a normalization of the convoy yield to $N(q_e)$, the normalization to $N(q_e-1)$, as suggested by Eq. (4), now displays a uniform, steep increase with decreasing q_e , as shown in Fig. 2 for O, Si, and Cl projectiles. To further test the relationship between $Y(q_e)/N(q_e-1)$ and σ_{ELC} , Fig. 2 also displays ELC and total loss [20] cross sections as far as available. A comparison between solid target and gas target data has to be viewed with the proper caution since ELC refers to electron loss from ground states which is not necessarily the case in foils. Total loss data include far more than just ELC events which only contribute within a narrow range of angles and emission velocities. In view of these limitations the agreement between the different data sets is surprisingly good. Introducing an even simpler model in which electron loss from highly excited states in collisions with neutral targets is treated in first Born approximation the total loss cross section can be written as [17]

$$\sigma_L = 4\pi Z_T^2 / \{ (v/d)^2 + q^4/4n^4 \}, \quad (5)$$

where d is the screening length of the target with nuclear charge Z_T . Eq. 5 is expected to be valid only for excited states with radii $\sim n^2/q$ large compared to d . If the ratio q/n becomes sufficiently large Eq. 5 can be further approximated by

$$\sigma_L = \text{const} \times q^{-4} n^4. \quad (6)$$

The overall agreement of the q^{-4} -dependence (solid black lines in Fig. 2) with the observed dependences is fair considering the narrow range of q values where the approximations leading to Eqs. (5) and (6) are expected to hold. For the lower charge states the agreement is reasonably good while it degrades for the higher charge states. This is due to shell effects for the higher charge states where the electrons are more deeply bound and Eq. (6) is no longer a valid approximation for the electron loss cross section.

The interpretation of the non-equilibrium data (Fig. 3a) relies on finding the appropriate source term for Eq. (2). Due to large experimental uncertainties introduced by only poorly defined target foil thicknesses, only a semiquantitative analysis can be performed. We note first that a comparison of the cusp shapes for C^{q_1+} ions incident on C foils with nominal thicknesses ranging from 1 to 10 $\mu\text{g}/\text{cm}^2$ displays no observable change in the cusp shape. This leads us to the assumption that for the foil thicknesses used in this experiment ELC can be viewed as the dominant mechanism in the production of convoy electrons.

We restrict ourselves in the following to a discussion of the thickness dependence of $Y(q_e=6)/N(q_e=5)$ for incident bare ions ($q_1=6$) and hydrogenic carbon ($q_1=5$). Other combinations can be analyzed along similar lines. For subequilibrium thickness the physical significance of the normalization to a x dependent charge state fraction $N(q_e=1, x)$ is no longer obvious because of memory effects on the charge state at distances $x' < x$ in Eq. (2). Furthermore, the population equilibrium in different shells of the projectile is established at different times,

i.e. within different mean free paths. Consequently, the distribution over excited states of a given charge state (q_e-1) changes over subequilibrium distances. Since theoretical calculations have shown that the ELC cross sections $\sigma_{\text{ELC}}(n=2)$ and $\sigma_{\text{ELC}}(n=1)$ for the velocity under consideration differ by almost an order of magnitude [3] it is necessary to treat the evolution of the ground-state population and of the excited-state population separately. We introduce in addition to λ_{CC} which characterizes the distance for equilibrating the overall charge-state fraction and is mainly determined by the evolution of the ground-state population a second mean-free path for excited-state (mainly $n=2$) equilibration, λ_{ce} . Accordingly, the source term for $q_1=q_e = 6$ which represents ELC from excited states in C^{5+} can be approximated by

$$R(6,6,x) = n_T \sigma_{\text{ELC}}^{\text{ex}} N_{\text{eq}}^{\text{ex}}(5) (1 - e^{-x/\lambda_{\text{ce}}}) \quad (7)$$

where $\sigma_{\text{ELC}}^{\text{ex}}$ denotes the ELC cross section from excited states and $N_{\text{eq}}^{\text{ex}}(q_e-1)$ denotes the equilibrium fraction for excited states of charge state q_e-1 . Inserting Eq. (7) into Eq. (2) leads to the convoy yield

$$\begin{aligned} Y(6,6,x) = n_T \sigma_{\text{ELC}}^{\text{ex}} N_{\text{eq}}^{\text{ex}}(5) \lambda_{\text{c}} \\ \cdot \left[1 - \left(1 + \frac{\lambda_{\text{ce}}}{\lambda_{\text{c}} - \lambda_{\text{ce}}} \right) \exp(-x/\lambda_{\text{c}}) \right. \\ \left. + \frac{\lambda_{\text{ce}}}{\lambda_{\text{c}} - \lambda_{\text{ce}}} \exp(-x/\lambda_{\text{ce}}) \right] \end{aligned}$$

while the x dependence of the charge-state fraction entering the normalization is given by

$$N(5,x) = N_{eq} (1 - e^{-x/\lambda_{cc}}) . \quad (9)$$

In the equilibrium limit, Eqs. (8) and (9) imply

$$\frac{Y(6)}{N(5)} = \lambda_{CNT} \frac{N_{eq}^{ex}(5)}{N_{eq}(5)} \frac{\sigma_{ELC}^{ex}}{\sigma_{ELC}} \quad (10)$$

which by comparison with Eq. (4) defines a crude approximation to $\bar{\sigma}_{ELC}$.

For incident C^{5+} ($q_1 = 5$), $Y(5,6,x)$ is again given by Eq. (8), however in general with a different value for λ_{ce} . On the other hand, the charge-state fraction is now approximately described by

$$N(5,x) = N_{eq}(5) + (1-N_{eq}(5))\exp(-x/\lambda_{cc}). \quad (11)$$

An estimate for λ_{cc} ($\approx 0.8 \mu\text{g}/\text{cm}^2$) can be taken from the simultaneously measured evolution of the charge-state fraction (Fig. 3b). A value for λ_{ce} can be inferred from the 4-state rate equation analysis for Oq^+ on C at 3 MeV/u by Schima et al [21] by adapting their ratio $\lambda_{ce}/\lambda_{cc}$. The use of the same ratio (≈ 0.5) for the present data (Cq^+ on C at 2 MeV/u) is justified since the equilibrium charge state fraction for bare, hydrogenic, and heliumlike are almost identical for the two systems. Furthermore, using a CDW approximation, we have found the cross section ratio for capture into hydrogenic excited states and into the ground-state to be approximately equal (within 20%). When choosing the isotachic inelastic

free-electron value [22] for the MFP for convoy electrons $\lambda_c \approx 0.4$
 $\mu\text{g}/\text{cm}^2$ and the same value λ_{ce} for both $q_1 = 5$ and 6 we can reproduce
 the thickness dependence of the convoy yield for $q_1 = 5$ and $q_1 = 6$
 fairly well (Fig. 3c) considering the large uncertainties in both the
 data as well as in the input parameter of the rate equation approach.
 The physical picture that emerges is the following: In both cases the
 convoy electron production proceeds through excited states in C^{5+} with
 approximately equal yield functions $Y(q_1, 6, x)$. The delayed rise of the
 coincident convoy yield for $q_1 = 5$ compared to $q_1 = 6$ results from the
 dramatic decrease of the normalization function $N(5, x)$ from unity to
 its equilibrium (≈ 0.35). A few remarks are in order: The model does
 not employ any adjustable parameters (except for the overall
 normalization to the equilibrium value $Y(6)/N(5)$ which does not
 influence the x dependence). The thickness dependence is determined by
 the characteristic distances λ_c , λ_{cc} , and λ_{ce} for which plausible
 measured or calculated input data are available. The present data give
 no indication for an enhanced mean free path of convoy electron
 compared to the inelastic MFP for free electrons. This differs from
 earlier measurements for higher q ions at higher velocities [12-14] in
 which larger sampling volumes in velocity space for the convoy yield
 have been used so that a direct comparison is not possible. This is
 not to say that for relatively low q values (≈ 5) Coulomb focussing
 becomes unimportant; in particular a modification of the elastic mean
 free path is very likely. Furthermore, it is worthwhile to point out
 that even if λ_{ce} and λ_c are of the same size as it is the case here
 the picture of a small likelihood of a change of the ionic charge

subsequent to convoy electron emission underlying the normalization to $N(q_e-1)$ of equilibrium data is still valid. The probability for a charge change is determined by the average cycle time for charge changing and not by a fast cycle involving excited states but running with a low efficiency. In the present case, for example, less than 15% of C^{6+} ions traveling in association with a convoy electron over distance $\lambda_C \approx \lambda_{Ce}$ are expected to have changed their charge again.

3. Conclusion

We have shown that data for convoy electron production after passage of multiply charged ions through foils for equilibrium as well as subequilibrium thicknesses can be interpreted as electron loss to continuum events involving predominantly excited states. The close kinship of convoy electron production and ELC in binary ion-atom collisions has been clearly established for equilibrium thickness targets and finds further support in the observations for non-equilibrium thickness targets. Further experimental and theoretical studies are necessary to solve several remaining puzzles, in particular a systematics for the enhanced mean free path of convoy electron λ_C as a function of the charge state q_1 , the projectile velocity v and the resolution volume in velocity space for convoy electrons is desirable.

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Figure captions:

Fig. 1: Typical velocity distributions of electrons in convoy (a), ECC (b), and ELC (c) cusps.

Fig. 2: Convoy electron yield measured in coincidence with ions q_e normalized to the number of exit charge state (q_e-1) for 0.5 MeV/u O, Si, and Cl ($\circ$), and 1.0 MeV/u Si and Cl, and 1.5 MeV/u O ($\square$) ions on 15 $\mu\text{g}/\text{cm}^2$ C foils. Also shown are total single electron loss cross sections for 0.5 MeV/u (O) and 1.5 MeV/u ($\square$) O ions of incident charge states q_e on N_2 and ELC cross sections for 2.5 MeV/u (Δ) Si ions of incident charge state q_e on Ar ——— Eq. (6).

Fig. 3: a) Normalized convoy electron yield $Y(q_e)/N(q_e-1)$ as a function of foil thickness for 2 MeV/u C^{q_i+} ions on C foils, (lines are drawn to guide the eyes).
b) Exit charge state distribution $F(q_e)$ as a function of foil thickness for 2 MeV/u C^{q_i+} ions on C foil (lines are drawn to guide the eyes).
c) Comparison of $Y(q_i, 6, x)/N(5, x)$ for $q_i = 5$ and 6 with the rate equation model (see text).

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