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Production and Transport of Convoy Electrons in Amorphous Carbon Foils

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Abstract

The production of free convoy electrons, emitted with velocities near the ion velocity in ion-solid collisions, is not well understood. Experiments concerning thickness-dependent yields have suggested the dominant mechanism for convoy production is electron loss to the continuum (ELC) in the bulk of the solid. Free electrons created in the bulk are subject to multiple elastic and inelastic scattering during transport through remaining layers of the solid. We discuss doubly-differential measurements of convoy electrons as a function of target thickness for fast O^{5+} ion projectiles incident on carbon foils of varied thicknesses. Angular distributions confirm the ELC model for convoy production. From the radial broadening of the convoy cusps we have determined energy and angular spreading parameters due to post-collisional multiple scattering.

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I. Introduction

In recent years a picture has been emerging of an abundant population of electrons characterized by high angular momenta that accompany an ion during its passage through a thin solid target. The experiments leading to this view have observed both X-ray [1] and convoy electron emission [2]. The convoy 'cusp' in secondary electron emission distributions produced by fast ions in foil targets exhibits the transverse signature of the projectile electron loss mechanism [3] and becomes enriched in higher-order multipoles with increasing projectile speed [2]. This can be interpreted as reflecting steady-state excitation of states having high n and ℓ (in an approximate hydrogenic basis) during passage through the bulk material, followed by electron loss processes which populate the cusp region of the spectrum (ELC). If this interpretation is correct, detailed measurements of the convoy electron cusp can, under appropriate circumstances, provide a probe of the state of excitation of charged particles penetrating condensed matter.

It is not yet clear how this high-ℓ population is formed, although there is general agreement that it is established in the bulk solid [1,2,4,5]; in the more general case of a projectile which brings electrons into the target one must consider competition between excitation from initially low n and ℓ and capture either directly into states of high angular momentum or into lower states, followed by excitation. The expected continuity of transition amplitudes across the ionization threshold of free ions [3] suggests a close connection between the above-mentioned experiments and those that detect large populations of high Rydberg states of projectiles emerging from the target [5]. Indeed, one might suppose a population of a complex of dynamic states in the solid analogous to Rydberg states in free atoms which relaxes upon exit from the target into free Rydberg states below threshold and continuum or convoy states of the projectile above threshold, the quantal version of the classical picture underlying the Monte Carlo stochastic perturbation calculations of Burgdörfer [6].

The experiments described in this paper address the questions of production of convoy electrons having high angular momenta, and of the transport of such electrons in thin solid foil targets. While the results presented are in preliminary form, they serve to define the nature of the problem, to contrast the transport of free electrons accompanied by a nearby projectile with the transport of unaccompanied free electrons, and to suggest future experimental parameters necessary to study the dynamics through which convoy electrons attain such high angular momenta.

II. Method.

Collisions of 115 MeV O^{q+} ions (projectile velocity $v_p = 17$ au), with q = 5, 6, 7, and 8 with self-supporting carbon foil targets were observed with an electrostatic spherical sector electron spectrometer equipped with position-sensitive detection (PSD) to provide angle-resolved emission distribution measurements. This portion of the apparatus has been previously described in detail [7]. A number of the targets used were of previously calibrated thickness and were used with an on-line Rutherford scattering monitor to estimate the thickness of initially uncalibrated foils. An electrostatic charge state separator was employed downstream of the electron spectrometer to measure charge state fractions of the emergent ions to assist in normalization of the convoy electron yields.

The output of the PSD system is decoded by a simple ratiometric method to recover the primary event position and thus the emission angles that, in combination with the spectrometer pass energy, determine the emission velocity components of the detected electron within limits imposed by finite resolution. The spectrometer energy resolution is 0.9% FWHM, and the angular resolution is about 0.5 deg. By scanning the spectrometer deflection field, the entire three-dimensional $\vec{v}$- distribution of the cusp can be obtained. Distributions differential in emission energy and polar angle are assessed for multipole content by means of a fitting procedure based on the expansion

$$\frac{d\sigma}{d\vec{v}} = \left(\frac{a}{v}\right) \sum_{k,j=0}^{\infty} B_{jk} \, v^{j} \, P_{k}(\cos\theta) \,, \tag{1}$$

where $\vec{v}$ is the electron emission velocity in the projectile rest frame, P_k are the Legendre polynomials, and B_{jk} are asymmetry parameters shown [3] to provide a close connection with population amplitudes of various ℓ-states that contribute to loss processes populating the convoy cusp, with high ℓ populations producing large moments of order k.

III. Results and Discussion

Figure 1 displays a selection of results of convoy cusp velocity distribution measurements. The data shown are contours of equal intensity in the emission-energy and polar-emission-angle plane for $v_p = 17.0$ au O^{5+} and O^{7+} ions incident on carbon foil targets. The axes are scaled so that equal intervals in either direction represent approximately equal intervals in longitudinal projectile frame emission velocity v_ℓ and transverse projectile frame emission velocity v_t. Fits are made to equation (2) convoluted with a spectrometer acceptance function in good agreement with recent computer modeling of our spectrometer [8].

A selection of resulting fitted values of B_{0k} (k = 1 to 4, 6, 8, and 10) are given in Table I for one-electron oxygen projectiles at v_p = 17 au. Fit results for other incident projectile charge states do not differ by a significant amount. The fits show no significant contribution from either B_{01} or B_{03} to the cross section, which we interpret to signify a prominent role for ELC in the convoy production process. The results agree with those of Berry, et al. [2] showing substantial higher-order multipole strengths, but we now find this true even for the thinnest self-supporting targets available. For thicker foils ($\gtrsim$ 10 μg/cm^2) this observation of high n,ℓ excitation within the target is in agreement with results of Betz, et al. [1] indicating that such high states, produced within the bulk, are required to explain long-lived cascade tails of foil-excited S^{15+} Ly α. Our observation of such higher-order multipoles in emission from thin foils (~1 μg/cm^2) shows that this excitation occurs within the first few layers of the target at these collision velocities. In fact, our data show little (if any) evolution in multipole content with increasing target thickness. This implies that the interactions which dominate the development of the ℓ-distribution have cross sections sufficiently large to produce mean excitation distances less than or on the order of the thickness of the thinnest target observed, and that we observe in the present experiment emission from an early-established nearly-equilibrium n,ℓ distribution.

Also listed in Table I is the isotropic B_{10} strength corresponding to the addition of first-order velocity corrections to the doubly differential cross section. Unlike the other parameters, this term shows a general increase with foil thickness, and corresponds to a gradual broadening of the emission distribution in the projectile frame - presumably due to elastic and inelastic scattering of the convoy electron distribution in the bulk of the solid. This effect is further demonstrated by the plot in Figure 2 of the emission contour widths for one-electron oxygen projectiles on foils of varying thickness.

IV. Conclusions

The observation of high n,ℓ excitation is in accord with earlier experiments [1,2] and with recent theory [6]. The rapidity with which an apparent equilibrium of such excitation is established is in at least qualitative agreement with the stochastic perturbation transport model [6]. Because it is not possible in the present experiment to observe the actual evolution of this excitation with target thickness, we are left to conclude that verification of the underlying model must await similar measurements with the thinnest available targets at substantially higher collision velocities.

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TABLE I. Results for selected fitting parameters $B_{j,k}$ in the case of O^{7+} projectiles at various target thicknesses.

	Nominal target thickness in $\mu g/cm^2$					
$B_{j,k}$	0.5	1.0	1.8	8.7	16	32
$B_{0,1}$	0.01	0.02	0.03	0.01	0.00	-0.09
$B_{0,2}$	-0.71	-0.77	-0.73	-0.78	-0.79	-0.82
$B_{0,3}$	0.01	0.02	-0.02	0.00	0.02	0.11
$B_{0,4}$	0.36	0.45	0.38	0.46	0.48	0.55
$B_{0,6}$	-0.18	-0.37	-0.30	-0.25	-0.25	-0.47
$B_{0,8}$	0.38	0.39	0.23	0.58	0.51	0.94
$B_{0,10}$	0.22	0.08	0.01	0.36	0.29	0.58
$B_{1,0}$	1.32	1.49	1.51	1.76	1.70	2.50

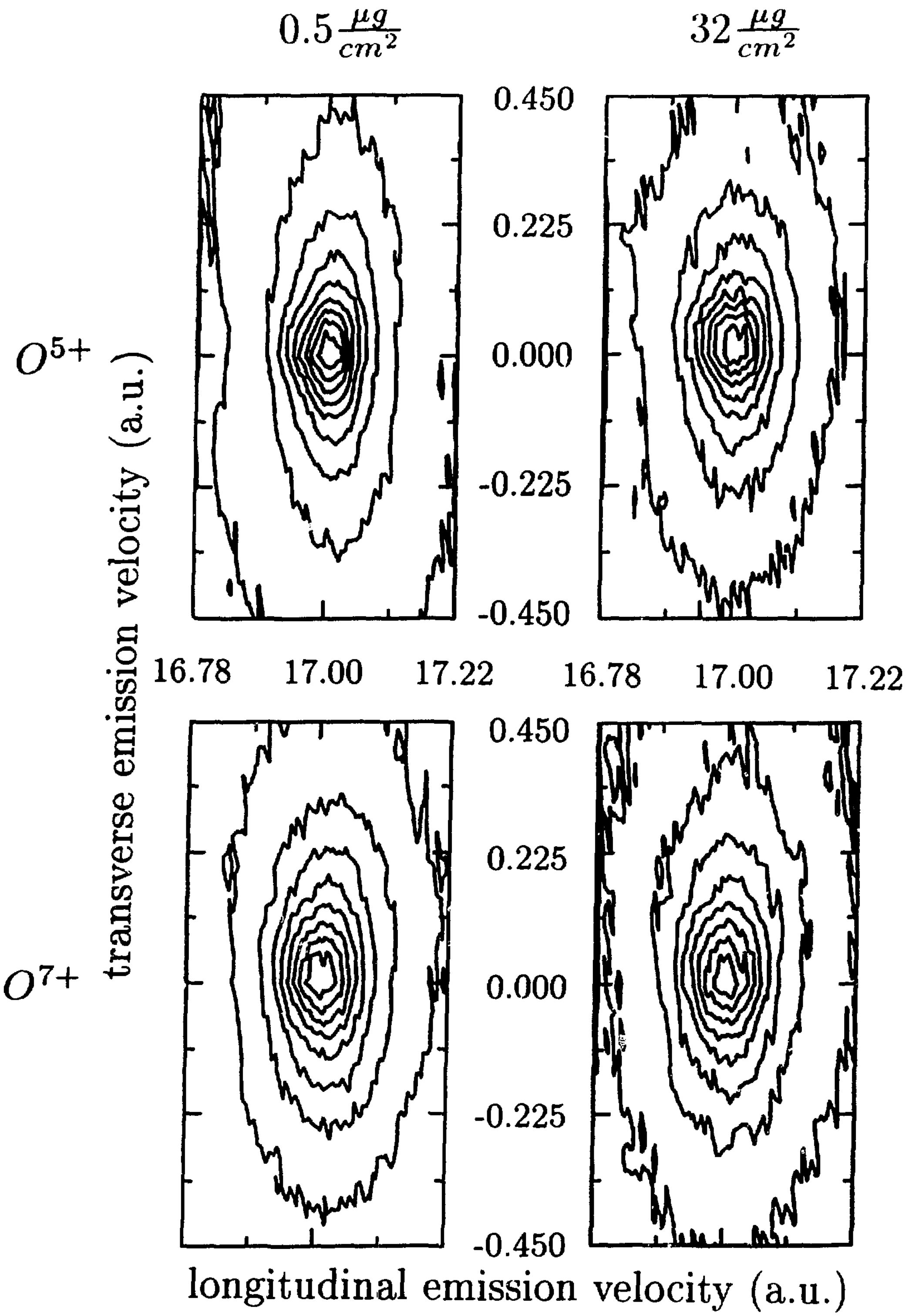
Figure Captions

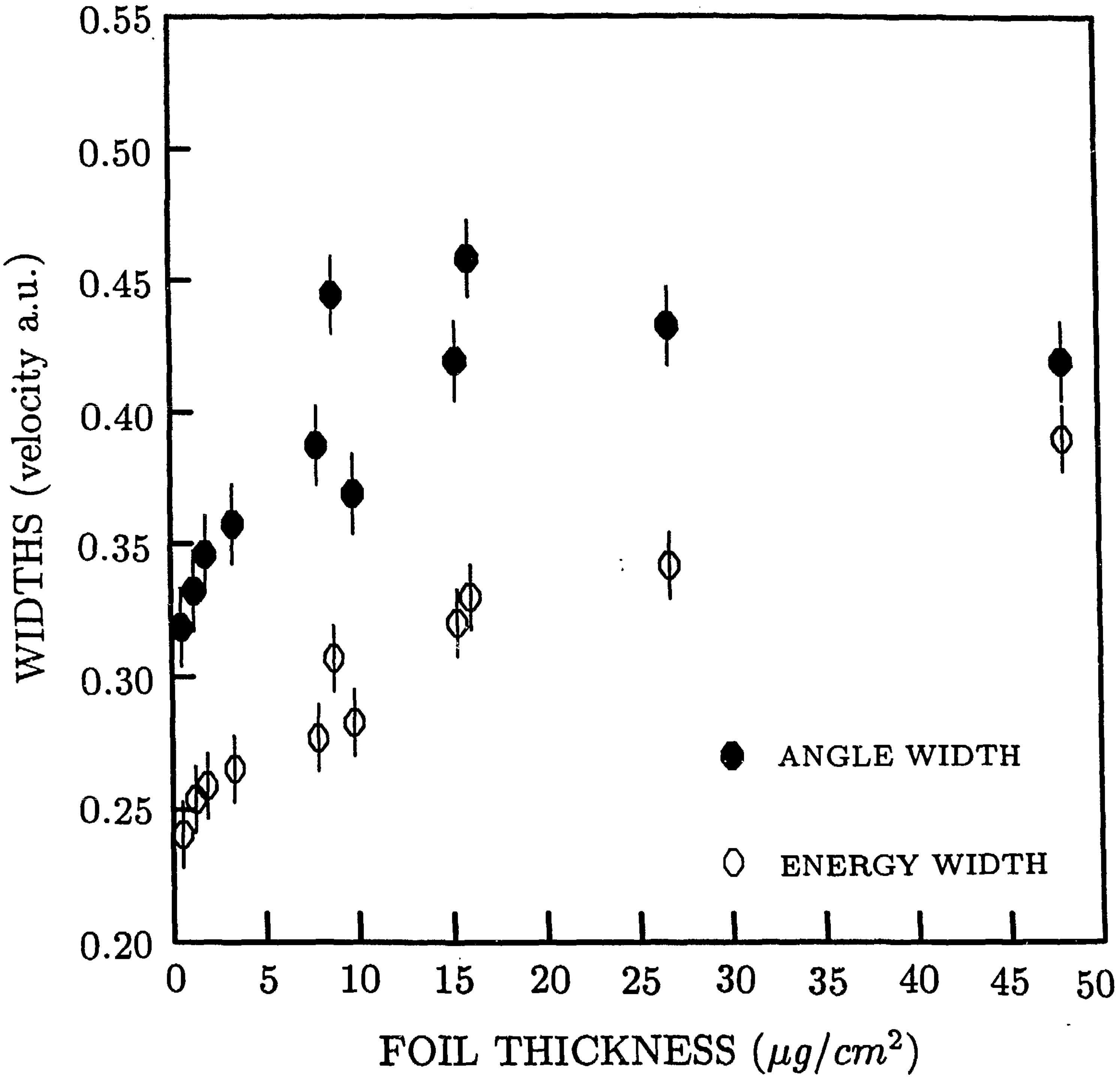
Figure 1.

Contour plots of equal convoy emission intensity for O^{5+} and O^{7+} at $v_p = 17.0$ au in carbon foils of nominal (uncalibrated) thicknesses 0.5 $\mu g/cm^2$ and 32 $\mu g/cm^2$. Contours shown represent multiples of 10% of the peak height. Scaling of the axes is chosen so that isotropic emission would produce essentially circular contours.

Figure 2.

Widths of the O^{7+} convoy distributions as a function of target thickness. The angular width is measured at the 50% contour (FWHM), but expressed as the equivalent projectile frame velocity ($= v_p \Delta\theta$). The energy width is similarly expressed in velocity units, and is measured at the 30% contour to avoid the dominance of the instrumental response near the singularity associated with the cusp.


$0.5 \frac{\mu g}{cm^2}$
$32 \frac{\mu g}{cm^2}$
O^{5+}
O^{7+}
transverse emission velocity (a.u.)
0.450
0.225
0.000
-0.225
-0.450
16.78
17.00
17.22
16.78
17.00
17.22
0.450
0.225
0.000
-0.225
-0.450
longitudinal emission velocity (a.u.)


WIDTHS (velocity a.u.)
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
5
10
15
20
25
30
35
40
45
50
FOIL THICKNESS ($\mu g/cm^2$)
● ANGLE WIDTH
○ ENERGY WIDTH