ANALYSIS OF EXPERIMENTAL VELOCITY DISTRIBUTIONS OF CONVOY ELECTRONS *

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Available data on the properties of velocity distributions of electrons accompanying ions in the velocity range from 1 to 5 au emerging from gas and solid carbon targets, for incident H^+ and H_2^+ beams, are presented in a consistent manner and compared with the theories of charge transfer to the continuum and of electrons in wake riding states trailing ions in solids.

Swift ions emerge from targets with convoys of electrons. Convoy electrons have distributions in velocity, v_e, relative to a peak velocity, v_p, which coincides within experimental accuracy with the velocity, v_i, of the ions [1,2]. A cut through the measured distributions, for example performed at half their peak value, in a plane containing the v_e-components that are longitudinal (parallel) and transverse (radial) to the ion propagation direction, typically has an oval shape. When the ion beam emerges from a solid, the larger axis is in the transverse direction [3]. In this letter we focus our attention on the lengths of the axes, that is the widths of the longitudinal and transverse velocity distributions, and their change with v_p.

The properties of convoy electrons have become the subject of active experimental research. The methods of data reduction are subtle functions of the experimental techniques, especially the resolutions in resolutions in energy and angle of the equipments used, and it is not always easy, at this early stage of the field, to compare in detail the convoy-electron properties reported in different laboratories. Cognizant of these difficulties we present a compilation and attempt a comparison of available data [1,3–6] for H^+ and H_2^+ beams incident on gas targets and on solid (carbon) foils, as displayed in figs. 1–3. Atomic units are used throughout.

The measured distributions have usually been compared with the predictions deduced from the process of charge transfer to the continuum (CTC): electrons ejected from the target by the ions make transitions into continuum states linked to the Coulomb potentials of the ions moving in vacuo [7–10]. If electrons move in bound states in the wakes of electron density fluctuations trailing swift ions, with $v_i > 1$, inside solids, these electrons may cross the surface of the medium without significant distortions of their momentum distribution [11,12]. The properties of convoy electrons coming from wake riding (WR) states were explored recently [13]. They differ significantly from those of CTC electrons. The characteristics of WR distributions should not appear at low ion velocities and after penetration of media, such as gases, where coherent wakes do not form.

The widths at half maximum (FWHM) of the longitudinal and transverse distributions, as obtained from WR [12,13], are:

$$F_\ell^{WR} = 2^{3/2}(\ln 2)^{1/2}[\alpha(v_p)]^{1/2} \quad (1)$$
$$= 1.67\, B^{1/4}(\omega_{res}/v_p)^{3/4}[\ln(4.49 B v_p/\omega_{res})]^{1/4},$$

$$F_t^{WR} = 2^{3/2}(\ln 2)^{1/2}[\beta(v_p)]^{1/2}$$
$$= 2.35\, B^{1/2}(\omega_{res}/v_p)^{1/2}\,. \quad (2)$$

Here ω_{res} is the collective plasma frequency and

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$B = Z_i^{eff} C\eta$. Z_i^{eff} is the effective charge of the ions in the medium, $C = \exp(-3\pi\gamma/4\omega_{res})$ accounts for the damping of the wake in the first trough and $1 \leqslant \eta < 2$ is determined by the correlation between the wake and the wake-bound electron [14]; $\alpha(v_p)$ and $\beta(v_p)$ are the longitudinal and transverse parameters of the wake-bound state defined in [12,13] [‡1].

The widths resulting from CTC are:

$$F_\ell^{CTC} = (3/2) v_p \theta_0 , \quad (3)$$

$$F_t^{CTC} \simeq 2.3\, v_p \theta_0 . \quad (4)$$

These widths are essentially determined by the instrumental longitudinal and transverse resolutions [3], the latter being given by $v_i\theta_0$, where θ_0 is the half angle of the angular acceptance cone of a particular equipment. In eqs. (3) and (4) the longitudinal resolution, as determined for example by the resolution of an electrostatic energy analyzer, is not accounted for. This is a fair approximation whenever the resolution volume in v_e-space (fig. 1 of ref. [3]) is a flat disc, as verified experimentally in refs. [1–5]. F_ℓ^{CTC} results from eq. (4.18) of ref. [4], F_t^{CTC} cannot be obtained analytically; the factor ($\simeq$2.3) multiplying $v_i\theta_0$ was obtained by numerical computation.

We observe from eqs. (1)–(4) that, while F_ℓ^{CTC} and F_t^{CTC} depend on θ_0, F_ℓ^{WR} and F_t^{WR} do not.

Fig. 1 shows how the longitudinal widths, given by eqs. (1) and (3), correlate with data from various laboratories. Gas-target measurements appear to agree rather well with CTC. The solid-target data tend to converge toward the CTC lines at low ion velocities; however it appears that the smaller θ_0, the less are the CTC lines correlated with the data. The WR curve is calculated for wake-riding in carbon as characterized by a collective resonance frequency $\omega_{res} = 0.74$ and a damping rate, γ, given by $\gamma/\omega_{res} = 0.78$ [15], resulting in a damping constant $C = 0.16$.

The experimental widths at half maximum of the transverse velocity distributions, F_t, are given by

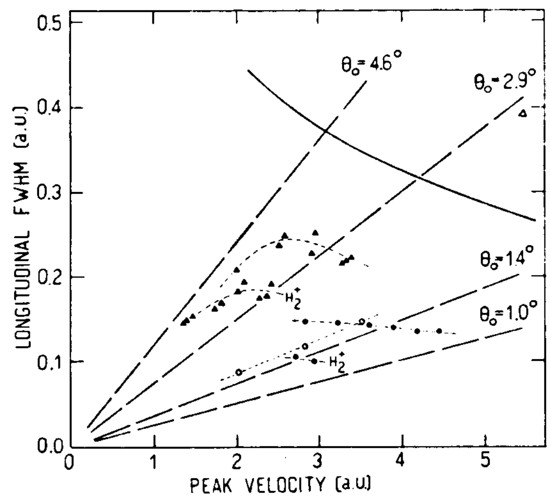

Fig. 1. FWHM of convoy electron longitudinal velocity distributions along the propagation direction of the ions versus peak velocity $v_p(\text{au}) = 0.271\, v_p(\text{eV})^{1/2}$, emerging from solids (carbon foils, solid symbols) and gases (open symbols), with ions from incident H^+ beams and, where indicated, from H_2^+ beams. Data from refs. [4] (acceptance angle $\theta_0 = 4.6°$; solid triangles), [3] ($\theta_0 = 1.0°$; solid circles), [5] ($\theta_0 = 2.9°$, Ne target; open triangle) and [1] ($\theta_0 = 1.4°$, He target; open circles). Dashed lines represent numerical CTC predictions for the respective θ_0 values, eq. (3), solid curve the WR prediction, eq. (1), for the carbon parameters [15] $\omega_{res} = 0.74$ and $\gamma/\omega_{res} = 0.78$. Dotted curves connect the data.

$F_t = v_p \theta^{FWHM}$, where θ^{FWHM} is the width of the angular distribution of convoy electrons measured at $v_e = v_p$ [3]. In fig. 2 these experimental widths are shown, as taken from refs. [3] and [6], together with the predictions of CTC and WR, eqs. (2) and (4). The CTC line corresponds to $\theta_0 = 1°$ [3]. Some of the data [6] do not report F_t explicitly, but values taken from angular spectra integrated over v_e. We judge that these values are still representative of F_t.

The F_t data as shown in fig. 2 are essentially independent of v_p. They span only an intermediate v_p range, and cannot as yet serve as a test to discriminate between different theoretical models.

The upper graph in fig. 3 displays the ratios F_t/F_ℓ. The measured transverse widths are some 80% larger than the longitudinal widths, almost independently of v_p. In judging the CTC prediction we have to bear in mind that the CTC ratio is determined by the relative importance of the transverse and longitudinal

[‡1] In ref. [12] eq. (4) should read correctly:

$$Wb \exp(-a)[1 - b \exp(b) E_1(b)] = 2 ,$$

and in eq. (6), α and β should be interchanged. In ref. [13] eq. (2) should read correctly:

$$\alpha = (k^2/8)[W \ln(W/2\Gamma)]^{1/2}, \quad \beta = (k^2/16) W ,$$

where $W = 16 Z_i^{eff} C\eta/k$, $k = \omega_{res}/v_p$, $\Gamma = 1.781$.

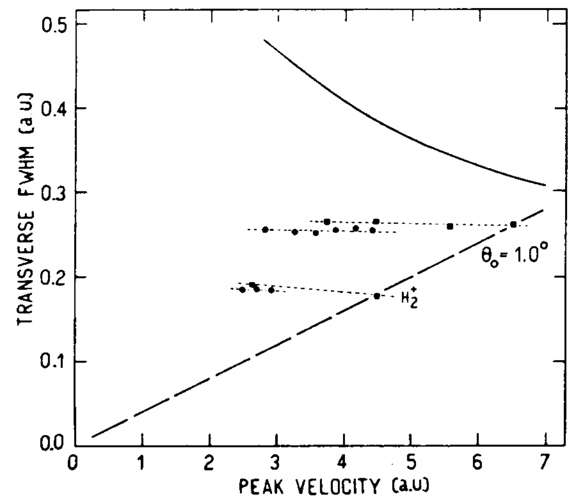

Fig. 2. FWHM of convoy electron transverse velocity distributions relative to the propagation direction of the ions, versus peak velocity v_p(au), emerging from carbon foils with ions from incident H^+ beams and, where indicated, from H_2^+ beams. Data from refs. [3] (solid circles) and [6] (solid squares). Dashed line is the CTC prediction, eq. (4), solid curve the WR prediction, eq. (2); dotted curves connect the data.

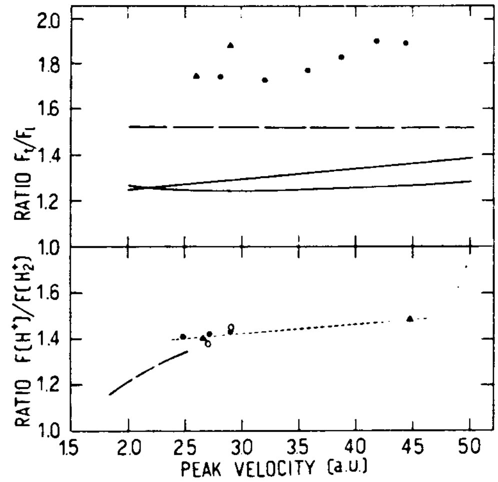

Fig. 3. Upper graph: Asymmetry in convoy electron velocity distributions expressed through the ratio F_t/F_ℓ. Data are for ions emerging from solid (carbon) foils from incident H^+ beams (solid circles) and H_2^+ beams (solid triangles) [3]. The CTC (dashed line) and WR (lower solid curve) ratios follow from figs. 1 and 2. The upper solid WR curve is calculated by including 1 eV [14] for the correlation contribution to the binding energy in the first wake-bound state. Lower graph: cluster effects in convoy electron velocity distributions as expressed through the ratio of the FWHM in both the longitudinal and transverse velocity distributions, measured with incident H^+ beams, to the FWHM measured with incident H_2^+ beams. The dashed curve represents smoothed data of longitudinal distributions [4]; open circles [3] are for longitudinal distributions, solid circles [3] and solid triangles [6] for transverse distributions. The dotted curve connects the data.

instrumental resolutions, the latter not being accounted for in eqs. (3) and (4). In the case of WR, the ratio resulting from the inclusion of a correlation-induced increment of the wake-binding energy of 1 eV [14] is also shown.

The lower graph of fig. 3 exhibits a cluster effect in the measured widths: convoy electrons emerging from carbon with ions from incident H^+ beams have a wider distribution of longitudinal and transverse velocities than those from H_2^+ beams. The ratios $F(H^+)/F(H_2^+)$ resulting from longitudinal and transverse widths are indistinguishable.

In our discussion angular and energy straggling of the ions, when leaving the foil, has not been accounted for. As shown in ref. [3], these effects tend to deteriorate the effective resolution of an experiment.

We do not stress the shape of the v_e-distributions as a criterion for the mechanism of convoy-electron production. Experimental resolution limits the identification of the CTC cusp in $|v_e - v_p|^{-1}$. The shapes of the distributions, if they originate in WR states, are related to the wavefunctions in the weak-bound states which so far have been calculated only in terms of gaussian trial wavefunctions [11,12]. Less localized trial wavefunctions would lower the WR curves in figs. 1 and 2.

Finally, we note that a small attenuation constant, C, as that of carbon is not favorable for wake-riding considerations. Materials with narrower plasma resonances and, hence, larger C would be more appropriate for further investigations. More high-resolution measurements of longitudinal and transverse velocity distributions, using gas and solid targets and covering a broad range of ion velocities, are needed to establish formly the trends emerging from the present data, and to cull the information they may contain about the states inside and outside the targets which determine the properties of the convoy electrons.

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