Z, Velocity, and Target-Material Dependence of Convoy Electrons from Solids

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(Received 19 June 1978)

We test the conjecture that convoy electrons emitted from solid targets originate from electrons bound in the potential wake trailing the traversing ion. Although we observe distinct differences in the longitudinal velocity distribution between solid and gaseous targets, we do *not* observe the predicted Z_1, velocity, and target-material dependences. From this we conclude that the majority of convoy electrons from solids do *not* originate from wake-bound electrons.

When swift ions penetrate gaseous or solid targets, they emerge with unbound electrons traveling in the direction, as well as with a velocity, coinciding with that of the incident ion. These electrons have been called convoy electrons. For gaseous targets this phenomena was first reported by Crooks and Rudd[1] and explained by Macek[2] as charge transfer to continuum states (CTC) associated with the Coulomb potential of ions moving in vacuum. Since that time other experimental as well as theoretical studies have been published.[3,4] The cardinal parameter for comparison of theory and experiment is the full width at half maximum (FWHM, in this paper referred to as $\Gamma_{l,v}$) of the longitudinal electron velocity distribution of the electrons emerging in the forward direction. In CTC theory $\Gamma_{l,v}$ can be expressed,[5] in atomic units, as

$$\Gamma_{l,v}{}^{\mathrm{CTC}} = \tfrac{3}{2} v_p \theta_0, \qquad (1)$$

where v_p is the projectile velocity in atomic units and θ_0 half of the acceptance angle, in radians, of the electron velocity analyzer. For gaseous targets, the experimental results[3,4] are consistent with Eq. (1); however, distinct differences concerning the yield, or cross section, have been reported.[6]

If the target is a solid medium one observes Γ's that are essentially independent of the velocity of the projectile.[3,4] These results are at odds with Eq. (1) and the assumption that the "last target layer"[7] is the source of the convoy electrons. A proposal has been advanced[8] that the convoy electrons from solids originate from electrons bound in the wakes of the electron density fluctuations trailing the swift ion in the solid. The properties of convoy electrons coming from wake-riding (WR) states are significantly different from CTC electrons. The FWHM of the longitudinal velocity distribution for WR electrons can be expressed,[5] in atomic units, as

$$\Gamma_{l,v}{}^{\mathrm{WR}} = 1.67 B^{1/4} \left(\frac{\omega_{\mathrm{res}}}{v_p}\right)^{3/4} \left[\ln\left(\frac{4.49 B v_p}{\omega_{\mathrm{res}}}\right)\right]^{1/2}, \qquad (2)$$

where ω_{res} is the material-specific plasma resonance frequency, $B = Z_1{}^{\mathrm{eff}} C\eta$, where $Z_1{}^{\mathrm{eff}}$ is the effective charge of the ion in the medium,[9] $C = \exp(-3\pi\gamma/4\omega_{\mathrm{res}})$ accounts for the damping of the wake through γ (the width of the plasma-frequency distribution),[10] and $\eta = 1-2$ is determined by the correlation between the wake and the wake-bound electrons.[8] In the WR description of convoy electrons the FWHM is determined by the characteristics of the target material (ω_{res}, γ) and the effective charge of the ion. It should decrease with increasing projectile velocity in contradistinction to Eq. (1).

The experiments reported in this Letter were designed to test these specific predictions by using various targets (C, Al, Ag, and Au), and large atomic numbers for the incident ions ($Z_1 = 1-28$) at high projectile velocities (6–14 a.u.). With these experimental conditions, one should form wakes during the traversal of the ion through the solid. Previous experiments with solid targets[3] were performed at lower projectile velocities (1–3 a.u.) where it is questionable if a wake is formed.[8] We find that there are distinct differences between solid and gaseous targets in agreement with other experiments,[3,4] but none of the predictions of the WR theory concerning the width of the longitudinal velocity distribution of convoy electrons is borne out.

The experimental arrangement is simple and straightforward. The ion beams (H_1^+, $E_1 = 2.5-3.86$ MeV/amu; O^{+q}, $E_1 = 1-3.86$ MeV/amu; Si^{+q}, $E_1 = 1-4.7$ MeV/amu; and Ni^{+q}, $E_1 = 1-2.5$ MeV/amu) of 10–20 pA intensity and various charge states were provided by the Brookhaven National Laboratory tandem accelerator. All ion beams were collimated to $\frac{1}{3}$ mm diam and $\pm 0.025°$ angular spread. It then traversed either a 4-mm thick gas cell terminated by a 2-mm aperture, or a solid target substituted for the gas cell. The emerging ion beam and the accompanying electrons then entered along the central ray of 180° spherical-sector analyzer of mean radius 3.8 cm, whose energy resolution $\Delta E/E = 1.4\%$ (FWHM) was set by a 0.72-mm analyzer exit aperture. The ion beam passed through an aperture in the larger radius plate of the analyzer and into a Faraday cup used for beam normalization. Standard electronic and multichannel scaling techniques were employed in collecting the data. The experimental chamber was surrounded by three pairs of mutually perpendicular Helmholtz coils, each of approximately 2 mm diam, to reduce the magnetic field in the electron analyzer region to less than 10 mG. Using this experimental arrangement we were able to measure the energy distribution of electrons emerging with the incident projectiles from gaseous or solid targets under similar experimental conditions.

A typical result, Fig. 1, shows the longitudinal electron velocity distribution, $d\sigma/dv_e$ (the distributions have been corrected for the variation in the acceptance energy, $\Delta E_e \propto E_e$, of the electron energy analyzer) for 108-MeV ($v = 12.4$ a.u.) Si^{+9} incident on 100-μg/cm^2 Au foil (as a solid line) and the normalized velocity distribution (normalization constant ~3) for 108-MeV Si^{+13} traversing 30 mTorr of argon. The dashed vertical line marks the velocity of the incident projectile. The velocity distribution observed from a solid target was independent of the incident silicon charge state q ($q = 6-14$), the velocity of the projectile, the target material, and the thickness of the target. Hence the solid line marks the typical distribution obtained with solid targets. Since the mean exit charge state from a solid of 108-MeV Si^{+q} is 12.9, a direct comparison between the electron distributions from the gas and the solid can be made. We note that they are distinctly different. For gaseous targets the velocity distribution (dashed line) exhibits a negative skewness (an asymmetry towards lower electron velocity). For solid targets the velocity distribution (solid line) is narrower, as measured by the FWHM,[11] and exhibits a positive skewness. This is a completely unexpected result not predicted by either the CTC[2,7] or WR[8] theories and can be indicative of the different processes of excitation for projectiles traversing solids and gases.

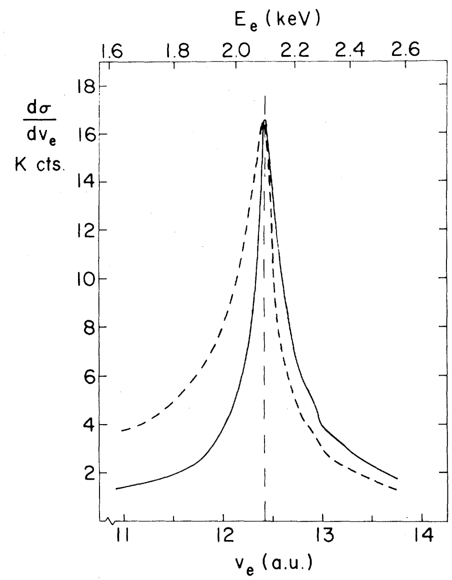

FIG. 1. The differential cross section $d\sigma/dv_e$ as a function of the electron velocity, v_e, of convoy electrons emerging at 0° with respect to the ion beam for 108-MeV Si^{+13} (dashed curve) on 30-mTorr Ar gas and Si^+ (solid curve) on 100-μg/cm^2 Au foil. The electron energy E_e is marked across the top of the figure.

Velocity distributions of the kind shown in Fig. 1 were collected for targets of C ($t = 30$ μg/cm^2), Al ($t = 50$ μg/cm^2), Ag ($t = 100$ μg/cm^2), and Au ($t = 100$ μg/cm^2) with the aforementioned ions. The target thicknesses were chosen such that there would be sufficient spatial extent to form a wake and that charge equilibrium would be achieved. We find the FWHM of the velocity distribution is, within experimental uncertainty, insensitive to the incident projectile, its charge state or velocity, as well as to the target material and its thickness. The results of about 80 measurements are summarized in Table I. The uncertainty in each measurement is estimated to be ±0.02 a.u., or 10%, arising from statistics, background subtraction, and instrumental resolution.[12] Although distinct trends appear, all of the data for solid targets can be represented, within experimental uncertainty, by a FWHM $\Gamma_{l,v} = 0.25 \pm 0.02$ a.u.

Comparison of the experimental results with CTC theory, Eq. (1), and WR theory, Eq. (2),

TABLE I. The measured full width at half-maximum, $\Gamma_{l,v}$ in atomic units, of the longitudinal velocity distribution of convoy electrons in the forward direction from thin solid targets. The energy range, in MeV per atomic mass unit, of the incident ions is indicated below the ionic species in parentheses. The material plasma frequency ω_{res}, in atomic units, and damping constant C, defined following Eq. (2), are listed, respectively, in parentheses below the target material. These numerical values are culled from Ref. 10. The bottom line lists the mean value of $\Gamma_{l,v}$ for a particular target material.

Target / Ion	C (0.74, 0.16)	Al (0.57, 0.90)	Ag (0.92, 0.009)	Au (0.95, 0.009)
H (2.5–3.86)	0.222 ± 0.02	0.212 ± 0.02	0.235 ± 0.02	0.228 ± 0.02
O (1–3.86)	0.230 ± 0.02	0.220 ± 0.02	0.232 ± 0.02	0.256 ± 0.02
Si (1–4.7)	0.260 ± 0.02	0.247 ± 0.02	0.258 ± 0.02	0.265 ± 0.02
Ni (1–2.5)	0.265 ± 0.03	0.270 ± 0.03	0.285 ± 0.03	0.287 ± 0.03
Mean	0.244 ± 0.025	0.238 ± 0.025	0.250 ± 0.025	0.261 ± 0.025

are shown in Fig. 2. The dashed line through the origin is the result of the CTC theory, Eq. (1), with an acceptance half-angle for the electron energy analyzer of $\theta_0 = 1.3°$. The results for gaseous targets (Ne and Ar) with O^{+8} and Si^{+14} projectiles are indistinguishable within experimental uncertainty (±10%) and follow the predicted velocity dependence of Eq. (1) in the velocity range of 8.7–12.4 a.u. About twenty-five measurements with gaseous targets and O^{+8} and Si^{+14} projectiles are represented by the three open points in Fig. 2. The light solid lines in Fig. 2 are the result of the WR theory, Eq. (2), for various incident ions, marked by Z_1, on an Al target. The material constants, ω_{res} and constant C, are shown in Table I. For C targets, Eq. (2) predicts values of Γ that are approximately 2/3 of those for Al. For Ag and Au targets, Eq. (2) predicts about equal values of Γ that are approximately 1/3 the Al values. The solid curve marked Ag is obtained from Eq. (2) for protons incident on Ag. The heavy solid line at $\Gamma_{l,v} = 0.25$ a.u. summarizes the present experimental results for solid targets shown in Table I. Clearly the experimental results disagree with the velocity dependence of the CTC theory [Eq. (1)], and with the Z_1, velocity, and target-material dependence of the WR theory as exemplified by Eq. (2). From this we conclude that the majority of convoy electrons from solids do *not* originate from wake-bound electrons trailing ions in solids.

Measurements of the longitudinal velocity dis-

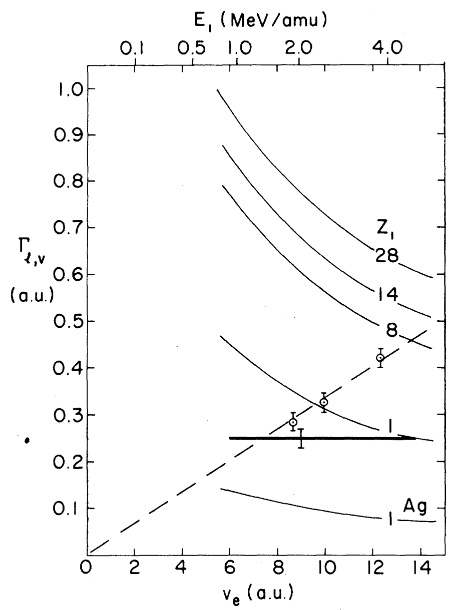

FIG. 2. The full width at half-maximum of the longitudinal electron velocity distribution, $\Gamma_{l,v}$, in atomic units for convoy electrons as a function of the electron velocity v_e, in atomic units. The incident projectile energy, in MeV per atomic mass units, is marked across the top of the figure. The dashed line, Eq. (1), is the CTC-state prediction. The solid lines, Eq. (2), are the predictions of the WR theory for an Al target with the indicated projectiles. The lowest solid curve marked Ag is the prediction of Eq. (2) for protons incident on Ag. The experimental data for solids, summarized in Table I, are represented by the heavy solid line. The open points represent the gas target (Ne and Ar) results for O^{+8} and Si^{+14}.

tribution of convoy electrons from solids disagree with predictions of CTC theory and with the conjecture that convoy electrons from solids originate from electrons bound in the wake of the trailing ion. It is evident from the present experimental results that further theoretical analysis of this phenomenon is required, and it is hoped that the present results will serve as a guide and stimulus.

We would like to thank the Brookhaven National Laboratory tandem accelerator staff for providing the required ion beams. We are also indebted to Dr. Krause of Oak Ridge National Laboratory for the use of the electron analyzer. One of us (R.L.) would like to acknowledge helpful discussions with N. Arista and W. Brandt of New York University. This work was supported in part by the Office of Naval Research, the National Science Foundation, and the U. S. Department of Energy.

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[11]We recognize that the measurement of the FWHM of a distribution that exhibits skewness introduces additional errors. However, an inspection of Fig. 1 concerning the magnitude of this error should convince the reader that the conclusions of this paper are not affected by this uncertainty.

[12]For a cusp-shaped (Ref. 7) electron velocity distribution the electron energy or velocity analyzer always measures an apparent FWHM, Γ', that is greater than the actual FWHM, Γ. We estimate $\Gamma'/\Gamma = 1 + \Delta E(4E\theta_0)^{-1}$, where $\Delta E/E$ is the FWHM of the energy resolution and θ_0 the acceptance half-angle, in radians, of the analyzer. For our analyzer, an acceptance half-angle of 1.3° and a measured energy resolution of $\leq 1\times10^{-2}$, $\Gamma'/\Gamma = 1.11$ and hence the results are within the quoted uncertainty.

Anisotropy in the Shape of the Electron-Hole-Droplet Cloud in Germanium

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(Received 1 May 1978)

Using a special infrared scanning technique we have produced photographs of the electron-hole–droplet cloud in unstressed Ge. Contrary to past beliefs, the cloud of droplets resulting from focused-laser surface excitation in neither spherical, hemispherical, nor cylindrically symmetric about the excitation point. The observed concentration of droplets along certain crystal-symmetry axes provides compelling evidence for a phonon wind which pushes droplets into the sample.

The nonequilibrium excitonic phases in semiconductors are commonly produced by surface excitation with photon energy much larger than the band gap. In high-purity germanium at low temperatures, the high-energy photoexcited carriers rapidly lose their kinetic energy by generating phonons, and within 10^{-9} sec they bind into free-exciton (FE) and electron-hole–liquid (EHL) phases.[1] These photoexcited states are conveniently studied by their characteristic LA-phonon–assisted recombination luminescence near $h\nu = 714$ and 709 meV, respectively, with lifetimes $\tau_{FE} = 2$–$10\ \mu$s and $\tau_{EHL} = 40\ \mu$s. Below 2 K and at moderate excitation levels, nearly all of the excitons have condensed into the lower-energy liquid phase.

The spatial distribution of electron-hole droplets produced by continuous point excitation has been a subject of considerable interest and importance. An argon laser beam with $h\nu = 2.41$ eV

