Observation of Two Components in the Velocity Spectra of Convoy Electrons Emerging with Protons from Aluminum Foils

A. Gladieux and A. Chateau-Thierry
Institut National des Sciences et Techniques Nucléaires, Centre d'Etudes Nucléaires de Saclay,
91191 Gif-sur-Yvette, France

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The velocity distributions of electrons emerging from aluminum with 0.5–1.4-MeV protons at similar velocities (convoy electrons) have two clearly separated components. The widths of the broad components have properties consistent with theories of charge transfer to the continuum. The narrow components behave very differently and might be indicative of solid-state effects.

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When fast ions emerge from solid or gaseous targets, they are accompanied by "convoy electrons"[1,2] that have velocities $\vec{v}_e$ close to the velocity $\vec{v}_i$ of the ions. During the past ten years, experimental and theoretical work[3-12] has explored the mechanisms underlying the characteristic cusp in the velocity distribution of these electrons. A useful parameter for the comparison between theory and experiment is the full width at half maximum (FWHM), $(\Delta v)_E$, of the velocity distribution of the electrons emerging in the forward direction.[8] According to the theory of charge transfer to the continuum (CTC),[5-7] in which the electrons of the target atoms are supposed to be transferred to continuum states of the projectiles in vacuo, $(\Delta v)_E$ is given by

$$(\Delta v)_E{}^{\rm CTC} = \tfrac{3}{2} v_i \Theta_0, \qquad (1)$$

where v_i is the projectile velocity and Θ_0 the acceptance half-angle of the electron spectrometer.

Results of experiment with gases[1-3,9,12] exhibit the linear dependence on v_i predicted by Eq. (1). The corresponding measurements with solids[1,2,4,5,8,9,12] do not indicate such a dependence of $(\Delta v)_E$ on v_i. An alternative mechanism takes into account the polarization wake trailing the ions inside solids in which electrons can be trapped. The FWHM of the longitudinal velocity distribution of such "wake-riding" (WR) electrons can be expressed, in units of $v_0 = e^2/\hbar$ and $a_0 = \hbar^2/me^2$, as[1,2]

$$(\Delta v)_E{}^{\rm WR} = 2^{3/2} v_0 (\alpha \ln 2)^{1/2}, \qquad (2)$$

where

$$\alpha = \frac{k^2}{8}\left[W \ln\left(\frac{W}{\sqrt{2}\,\Gamma}\right)\right]^{1/2}, \qquad (3)$$

with

$$W = 16 Z_1{}^{\rm eff} C \frac{\eta}{k} \qquad (4)$$

in which $Z_1{}^{\rm eff}$ represents the effective charge of the ions, C is a constant related to the damping of the wake, $k = (\omega_{\rm res}/v_i)a_0$ is proportional to the plasma frequency $\omega_{\rm res}$ of the medium, $\Gamma = 1.781$ and $\eta = 1-2$ is determined by the correlation between the wake and the wake-bound electrons. Laubert *et al.*[9] have performed extensive experiments as a function of Z_1, the projectile velocity, and the solid target material. They concluded that none of the predictions of the CTC or the WR theories concerning the width of the longitudinal velocity distribution of convoy electrons is borne out by their findings.

The experiments reported in this Letter pertain to the measurements of $(\Delta v)_E$ for the convoy electrons emitted from 15 μg/cm^2 Al foils with protons at emerging energies $E_1 = 0.5$, 0.8, 1.0, and 1.4 MeV. The investigation was motivated by the difficulty of understanding why neither of the two theories are able to explain the results with solids. Why does the interaction of the ions with the last atomic layer of a solid not give rise to CTC electrons? Why is the existence of wakes trailing behind the ions, so effective in explaining the molecular ion-foil interactions,[13] not expressed, even partially, in the convoy-electron production? As a matter of fact, the present experiments show evidence that two mechanisms take part in the production of convoy electrons.

The experimental arrangement is described. A proton beam delivered by a 2 MV Van de Graaf accelerator was momentum analyzed and collimated to 0.1-mm diam and ±0.005 degree angular spread. It then traversed a 15 μg/cm^2 Al target and entered, together with the convoy electrons, along the central axis of a 160° spherical-sector spectrometer[14] of mean radius 36.5 mm. The energy resolution for the electrons, $\delta E/E \simeq 0.2\%$, was set by a 0.1-mm-diam exit diaphragm and the size of the spot on the target. A second

0.2-mm-diam diaphragm downstream fixed the acceptance half-angle of the electron energy analyzer at $\Theta_0 = (0.57 \pm 0.08)$ degrees. The proton beam, after transmission through the Al foil, passed through a slot in the external plate of the spectrometer and was registered in a Faraday cup for beam normalization. Electrons were counted in a channeltron located behind a 2-mm-diam diaphragm biased at −15 V to suppress the secondary electrons created by the exit diaphragms. The input end of the channeltron was biased in such a way that, for any electron energy, the apparent energy seen by the channeltron was 1000 eV, thus keeping the detection efficiency constant. The bias of the output end was varied in the same way in order to keep the multiplication gain constant.

The spectrometer region was surrounded by three mutually orthogonal pairs of Helmoltz coils, each of 1.5 m in diameter, thus reducing the magnetic field to a few milligauss. The target chamber was evacuated to 10^{-8} Torr. The spectrometer together with the channeltron and its preamplifier were mounted on a goniometer which permitted alignment to within ± 0.025 degree. The determination of the position of the counting peaks for convoy electrons ranging from 150 to 850 eV ($3.3 \leq v_e/v_0 \leq 7.9$) permitted a check of the linearity of the spectrometer with an analyzer constant of (0.4380 ± 0.0002) V/eV.

The resolution of the spectrometer was measured independently by injecting monoenergetic electrons of velocities comparable to the peak velocity of the convoy electrons from a tungsten filament through a biased slit system. For a given electron velocity v_e, the width of the resolution function was found to be $\delta v_e/v_i = 1 \times 10^{-3}$.

The results are shown in Fig. 1. The four convoy-electron velocity distributions are displayed as a function of the velocity differences $v_e - v_i$ in atomic units ($v_0 = 2.18 \times 10^8$ cm/sec). The background was $\lesssim 5\%$ and flat at these high velocities, as indicated by the dotted area. This background was subtracted from each measurement. The resulting distributions are shown on the same ordinate scale displaced upward for clarity. The resolution function measured for the lowest spectrum is indicated by the cross-hatched peak. Each curve gives clear indications of a two-component phenomenon. A narrow component appears to be superimposed on a wide component, as sketched by the dashed lines. The dashed lines represent approximately what one would expect from a cusp for the broad component according

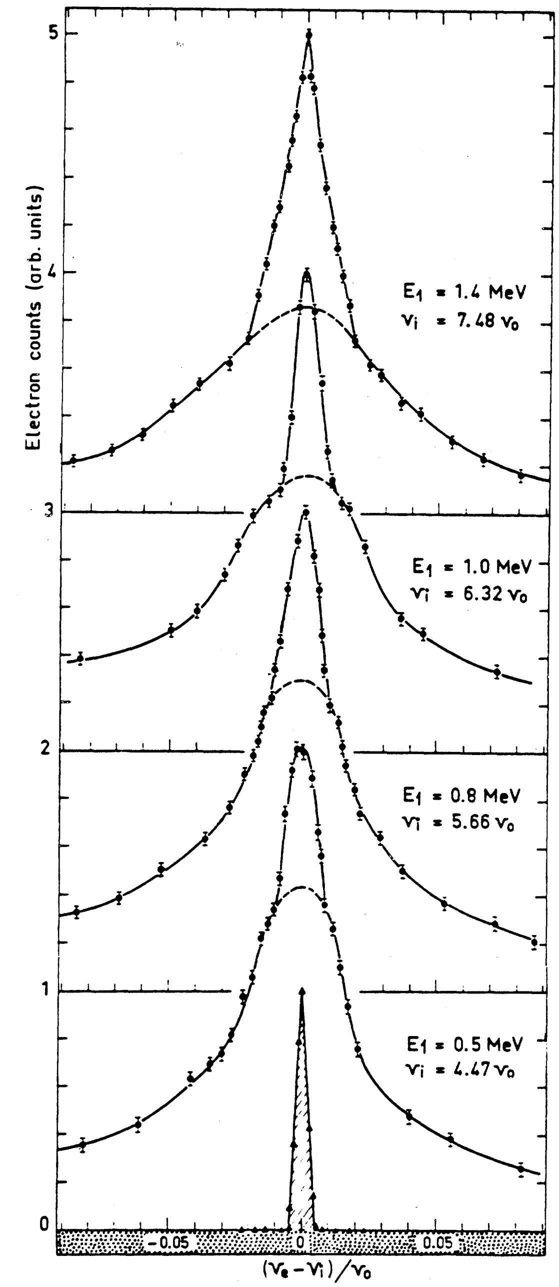

FIG. 1. Velocity distributions of convoy electrons emerging with H^+ projectiles from Al along the beam direction as a function of the difference between the electron velocity, v_e, and the proton velocity v_i. The 5% background (dotted area) was substracted from all points. The FWHM of the resolution function is measured to be $\delta v_e = 1 \times 10^{-3} v_e$, as illustrated by the cross-hatched area under the measured resolution function pertaining to the convoy-electron velocity distribution for $E_1 = 0.5$ MeV. The solid lines are drawn to guide the eye. The curves for other E_1 values are displaced upward by one unit on the ordinate for clarity. The separation into a wide and a narrow component, as described in the text, is indicated by dashed lines.

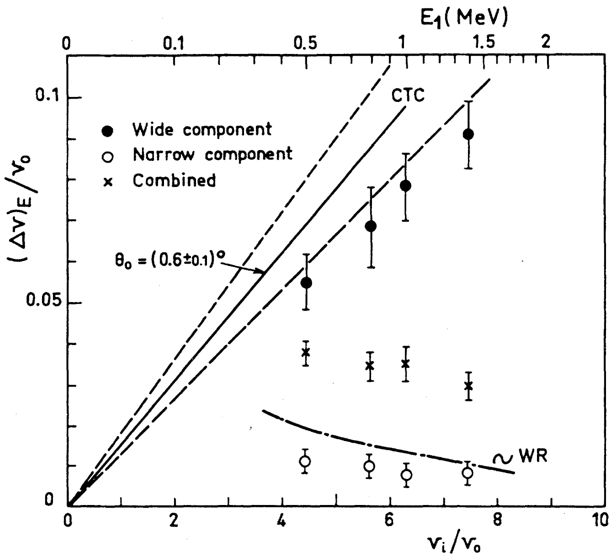

FIG. 2. The FWHM, Δv_E, of the convoy electron velocity distributions shown in Fig. 1, corrected for the spectrometer resolution. The widths before separation into a wide and narrow component are given by the crosses. When decomposed, the widths of the wide components (solid symbols) follow the CTC theory as expressed by Eq. (1), for our detector acceptance angle $\Theta_0 = (0.6 \pm 0.1)°$. The widths of the narrow components (open symbols) are insensitive to the projectile velocity v_i, and are comparable to the uncertainty in the momentum of wake bound electrons.

to the CTC theory folded in with our resolution functions. In fact, the widths of the broad components follow the velocity dependence of the CTC theory as shown in Fig. 2. The wide components are asymmetric toward lower velocities in ways similar to results obtained with gas targets.[15]

The narrow components appear to be symmetrical. Their relative intensity increases with v_i. Their widths are insensitive to v_i as displayed in Fig. 2. They thus have properties similar to those of the spectra observed by Breining *et al.*[16] in noble gases with clothed heavy ions and attributed there to electron loss to the continuum. The probability of a proton capturing an electron under these conditions,[17] which then could be lost to the continuum, is $\sim 10^{-3}$. We attribute the narrow components reported here to a solid-state effect. Judging by the uncertainty relation, the width for electrons that ride in a density wake trailing the projectile, of dimension $\sim \pi v_i/\omega_{\rm res}$, in Al is of order $\Delta v_E^{\rm WR} \approx 0.1 v_0/v_i$, as sketched with a curve of dots and dashes in Fig. 2. The WR theory as applied in Refs. 1 and 2, however, yields $\Delta v_E^{\rm WR}$ values that are more than ten times larger. This leaves unsettled the questions concerning the mechanism giving narrow components. If one were not to decompose the spectra into two components, the Δv_E are similarly independent of v_i as indicated by the crosses in Fig. 2.

The large disparity in the behavior of the wide and narrow components, as resolved here in the velocity distributions of convoy electrons from aluminum, suggests that the extended measurements with other solids and projectiles now in progress in our laboratory will sort out to what extent the wide components might indicate surface effects and the narrow components solid-state effects in the bulk of the material as they are set in motion by atomic projectiles.

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