Experimental evidence of beam-foil convoy electrons being produced by an electron transfer to the continuum mechanism

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The origin of beam-foil convoy electrons has been a subject of many controversial interpretations and discussions. In this work, velocity distributions of electrons ejected into the forward direction from a carbon-foil target have been measured with incident proton beams of energies between 60 and 300 keV, and under the same experimental conditions as equivalent measurements recently performed in this laboratory with a He-gas target. Cusp widths are discussed as a function of projectile velocity and instrumental angular acceptance by taking fractional peak heights from the base line as well as by previously subtracting a background obtained by joining peak tails. It is concluded that neither of these procedures is valid. On the other hand, measured electron spectra can be well fitted in terms of a general parametric expression of the scattering amplitude for an electron transfer to the continuum process. The absence of a strong negative cusp skewness, as was observed with the gas target, hints in the direction of an electron loss rather than an electron capture to the continuum process. A significant background contribution that is absent for a single-collision electron transfer to the continuum process is interpreted as due to the emission of secondary electrons that are not correlated to the emerging projectiles.

INTRODUCTION

When an ionic beam interacts with a gas or solid-foil target a strong increase in the production of unbound electrons occurs when their velocity $\vec{v}$ approaches that of the emerging ions $\vec{v}_i$, that is, when the velocity $\vec{v}\,'=\vec{v}-\vec{v}_i$ as seen from the moving ion is small. This gives rise to the observation of a characteristic cusp-shaped peak in the measured distribution of electrons as a function of angle and energy. The process is known as electron transfer to the continuum (ETC); electrons that travel in the continuum of the emerging ions are called "convoy electrons." The subject of electron transfer to the continuum in gaseous and solid targets has been discussed in several review articles.[1,2,3,4] For low-density gas targets the production of these electrons by single collisions has been described theoretically in terms of the Coulomb attraction of the electron by the moving ion. The origin of the ejected electron may be electron capture to projectile continuum states (ECC) from a bound state of the target[5] or electron loss (ELC) from a bound state of the projectile.[6]

Dettmann *et al.*[7] attributed the production of beam-foil convoy electrons to a single-collision process in terms of ECC produced in the last layers of the solid. On the other hand, a mechanism based exclusively on the collective interaction of the moving ion with the electron plasma of the solid has been proposed[8]: electrons are supposed to ride the wake in potential wells traveling behind the ion moving through the solid. When comparing these theoretical models with experimental information a controversy arose with respect to the correct evaluation of widths of measured electron distributions[9,10,11] which essentially has to do with the correct evaluation of a possible background contribution underlying measured convoy-electron distributions. There is now agreement that the peak shapes and widths predicted by the model of wake riding are not in agreement with experimental evidence. Another possible origin of beam-foil convoy electrons that has been suggested is ELC of an electron which has been captured in a bound state of an ion before it emerges through the solid surface.[3]

A common feature of ETC theories is that the cross section of the production of convoy electrons can be expressed as[3]

$$\frac{d\sigma}{d\vec{v}}=|f_c(v')|^2F(v_i,\vec{v}\,') , \tag{1}$$

that is, by the product of the square of a Coulomb factor contained in a hydrogenic continuum orbital around the projectile times a function F which depends on the electron velocity $\vec{v}\,'$, and that, therefore, ETC theories may introduce asymmetries into the cross section. For small v' Eq. (1) has been approximated by[7]

$$\frac{d\sigma}{d\vec{v}} \simeq \frac{2\pi Z'}{v'} F(v_i) \tag{2}$$

which leads to a spherically symmetric cross section. Here Z' is the atomic number of the projectile. We observe that $d\sigma/d\vec{v}$ diverges as $1/v'$ when $v \rightarrow v_i$. Therefore, angular and energy acceptances of electron spectrometers used in performing measurements are decisive in determining the shape of measured spectra. These acceptances can be represented in the velocity space ($\vec{v}$) of the ejected electrons by a "resolution volume"[9,12] given by a cylinder of height $2Rv$ and diameter $2\theta_0 v$. Here $R = (\Delta v)_{\mathrm{HWHM}}/v$ is the experimental relative velocity resolution and θ_0 is the half angle of the cone into which electrons are accepted. When $R \ll \theta_0$ cusp-shaped peaks result if the electron distribution is measured "longitudinally," i.e., in the direction of the incoming ion beam. When using the simplified cross section given by Eq. (2) the full width at half maximum (FWHM) of these cusps can be written as[7]

$$\Delta v = \tfrac{3}{2} v_i \theta_0 \ . \tag{3}$$

Recently in our laboratory a detailed experimental study of convoy-electron cusps produced by ECC was performed for the $H^+ \rightarrow$ He system and reported in a paper[12] that subsequently will be quoted as I. For the first time, this study contained not only the dependence of peak shapes and widths on v_i but also on θ_0. Peak asymmetries, characteristic for the ECC process, were observed and discussed in terms of a parametric expansion of the cross section $d\sigma/d\vec{v}$. In spite of these asymmetries, at sufficiently large ion velocities the proportionality of cusp widths to $v_i\theta_0$ was conserved.

The purpose of the present work was to perform an equivalent experimental study for the case of electrons emitted downstream from a carbon foil traversed by hydrogen projectiles. In particular, it was our purpose to shed some light on the much discussed problem of correct background treatment.

MEASUREMENT AND DISCUSSION

The equipment used was identical to that described before (see Fig. 2 of I). The gas target was now replaced by a carbon foil of 2 μg/cm^2 thickness, as specified by the manufacturer.[13] As explained in I, the angular acceptances of the electron spectrometer were selected as $\theta_0 = 0.2°$, 0.5°, 1.0°, 1.5°, 2.0°, and 2.5° by a set of interchangeable orifices which intercept and define the emerging electron beam.

A typical spectrum is shown in Fig. 1. As in I, the instrumental background obtained with "target out" was negligible. This, however, does not rule out the possibility of an additional instrumental background that only appears when the target is in place and may be due to stray electrons produced by the ion beam in this target, which, even if their emission angle and energy do not agree with the setting of the spectrometer, may find their way to the detector. However, the measurements performed in I resulted in peaks whose tails were so low that no background had to be considered. As the only change made was to replace the gas by a solid-foil target, we assume that this additional instrumental background contribution could be neglected.

A set of six cusps obtained by using the angular acceptances specified above and normalized at the peak top is seen in Fig. 2 for a proton beam of 192 keV. Such sets of cusps have been measured at nine ion energies between 60 and 300 keV, i.e., ion velocities between 1.5 and 3.5 a.u. Figure 2 is to be compared with Fig. 5 of I. In the first place, we observe that the beam-foil convoy-electron cusps obtained with the same angular resolutions are broader than those resulting from ECC in He gas. For the case of heavy-ion projectiles Laubert *et al.*[14] report narrower peaks in the beam-foil case. Second, it is again seen that the cusps become broader with increasing angular acceptance. However, differing from what has been observed in I for the case of a gas target, the peak tails become almost horizontal, their height being an increasing function of θ_0. Furthermore, the large asymmetries towards lower v observed for the ECC spectra in I are not seen, but a slight skewness towards low v is still detectable.

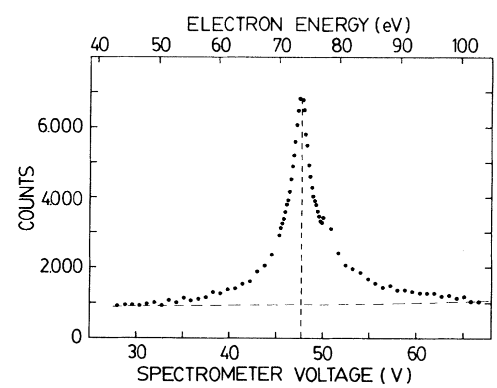

FIG. 1. Typical convoy-electron spectrum measured with a proton beam of $E_i = 134$ keV that emerges from a carbon foil of 2 μg/cm^2 thickness; $\theta_0 = 0.2°$. Also shown is an apparent background that results from joining peak tails.

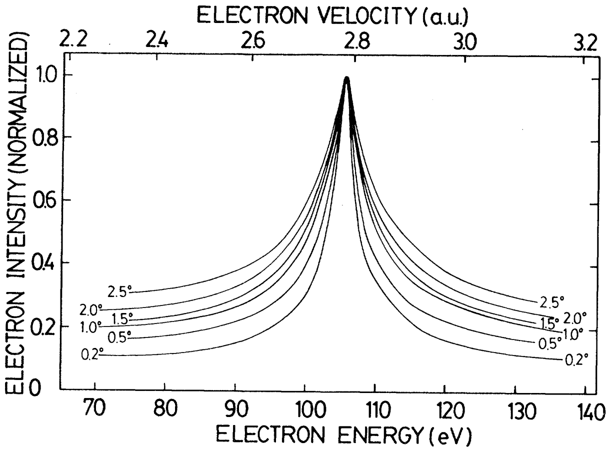

FIG. 2. Set of experimental cusps, obtained at $E_i = 192$ keV, for the different angular acceptances θ_0 shown. Spectra are normalized to 1 at the peak tops.

This differs from beam-foil electron cusps obtained with heavy ions which show a slight skewness towards higher velocities.[14,15] A minute rounding at the top of the peaks in Fig. 2, which was not detectable in the case of the ECC cusps obtained with the He-gas target, can be attributed to energy straggling of the protons in the solid target.

We now proceed to discuss the measured peak shapes in terms of the empirical parameters, width and skewness. For this purpose we transform the electron distribution Q^*, measured as a function of the electron energy E_e, into Q^*/v given as a function of the electron velocity. For single collisions we have

$$\frac{Q^*}{v} \propto \frac{Q}{2Rv} = \left.\frac{d\sigma}{dv}\right|_{\theta_0}, \tag{4}$$

where Q is the electron distribution defined by Eq. 8 of I and

$$\left.\frac{d\sigma}{dv}\right|_{\theta_0} = 2\pi \int_0^{\theta_0} v^2 \frac{d\sigma}{d\vec{v}} \sin\theta \, d\theta \ . \tag{5}$$

Let us call $v_p = v_i$ the electron velocity at the peak top; v_- and v_+ are the velocities at half the peak height for the low- and high-velocity peak tails, respectively. Then (as in I) the partial and total cusp widths can be written as

$$\begin{aligned} \Delta v_- &= v_p - v_- , \quad \Delta v_+ = v_+ - v_p , \\ \Delta v &= v_+ - v_- = \Delta v_- + \Delta v_+ \ . \end{aligned} \tag{6}$$

As a measure for the peak asymmetry we again introduce the "skewness"

$$r = \frac{\Delta v_-}{\Delta v_+} \ . \tag{7}$$

When discussing ETC spectra and comparing them with theory it has been a practice used by many authors to subtract an "apparent" background obtained by joining the tails of measured cusps in a streamlined fashion, as shown in Fig. 1. Steckelmacher *et al.*[10] have emphasized that this procedure is certainly not correct in the case of single-collision ECC processes for which a unique origin of the emitted electrons must be considered. However, in the case of a solid-foil target one cannot make the *a priori* assumption of single collisions and unique origin of the electrons. It is important to bear in mind that electrons which have been produced by collisions inside a solid target can be emitted through the surface after having lost, by scattering and energy degradation, their correlation to the ionic projectiles. These "secondary electrons" may produce a background that is additive to the convoy-electron emission process.[3]

Let us now tentatively represent the peak widths Δv, measured at half the peak heights, as a function of v_p and θ_0. We do this by measuring these peak heights from the base line as well as by previously subtracting the apparent background obtained by smoothly joining the peak tails, as seen in Fig. 1. We purposely try both methods in order to see if, using the same experimental data, previously reported discordances of width dependences on v_i are confirmed. Furthermore, our equipment permits us to perform an equivalent study of the width dependences on the experimental angular acceptance (θ_0). The resulting FWHM which we call Δv_s (apparent background) subtracted) and Δv_b (background included) are represented in Figs. 3(a) and 3(b). The linear dependences as predicted by Eq. (3) for $v_p = v_i$, and confirmed experimentally for gaseous targets,[16,12] are also shown in this figure.

In accordance with previous evidence we observe in Fig. 3(a) that Δv_s results independent of v_p.[9,14] This behavior has been used as an argument against the origin of beam-foil convoy electrons from a single-collision equivalent ECC process.[9] In Fig. 3(b) we observe that the peak widths Δv_s, measured as a function of the angular acceptance, also depend only slightly on θ_0. As a matter of fact, with increasing θ_0 they tend towards a constant value.

On the other hand, it is seen in Fig. 3(a) that at the higher ion velocities covered in this study the widths Δv_b increase with increasing v_i but are larger than those predicted by Eq. (3). In a range of still higher v_i Steckelmacher *et al.*[10] found agreement with the proportionality of cusps widths to v_i. They measured these widths at a fractional peak height of 70% taken from the base line. In Fig. 3(b) we see that also as a function of θ_0 the widths Δv_b are larger than those predicted by Eq. (3). They are

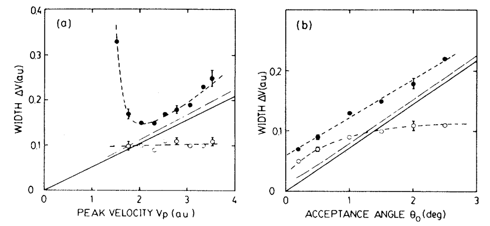

FIG. 3. Cusp HWHM, Δv: (a), plotted as a function of v_p for $\theta_0 = 2°$; (b), as a function of θ_0 for $v_p = 2.78$ a.u. (○) Δv_s, data obtained with apparent background subtracted; (●) Δv_p, with background included, (— —) widths calculated including angular dispersion and energy straggling of ion beam.

found to approximately obey a dependence of the form

$$\Delta v_b \cong \tfrac{3}{2} v_i \theta_0 + C \tag{8}$$

with C a function of v_i.

One's first thought could be to assign the above discrepancies between the measured Δv_b and Eq. (3) to the finite resolution in energy of our electron spectrometer along with angular dispersion and energy straggling of the projectiles by multiple collisions in the foil target. The latter produce an increase in the effective acceptances θ_0 and R which determine the resolution volume in velocity space. For the specified foil thickness (2 μg/cm^2) we computed the contributions to θ_0 and R from these effects by using tables of Sigmund and Winterbon and Biersack *et al.*[17] and added them quadratically to the values that are characteristic for our electron spectrometer. In this way the slightly rounded peak tops, as seen in Fig. 2, resulted because the condition $R/\theta_0 \ll 1$ that leads to cusp-shaped peaks is not rigorously fulfilled (in our case $R/\theta_0 \simeq 0.08$ for the lowest ion energy of 60 keV). It can, however, be shown that even if $R \ll \theta_0$ is not verified the resulting ETC peak widths are still proportional to $v_i\theta_0$, that is, $\Delta v = a v_i \theta_0$ with $a > \frac{3}{2}$.[11] In Figs. 3(a) and 3(b) the theoretical width dependences, corrected for the finite instrumental acceptance in energy plus the angular dispersion and energy straggling of the ions, are also shown; they do not account for the discrepancies of the measured peak widths (Δv_b) with theory.

In Fig. 3(a) it comes to one's attention that in the lower velocity range of our measurements we observe a steep increase of Δv_b with decreasing v_i, the dependence that is expected for the ETC process being reversed. Such an increase is not seen for Δv_s. This behavior is understood when we look at Fig. 4 where, for the case $\theta_0 = 2°$, we represent all the measured cusps together. These spectra are compatible in that they are normalized to the collected beam charge. It is obvious that there is an apparent background contribution that is common to all the measured spectra. An increase of this background with decreasing peak velocity $v_p = v_i$ is evident. When determining cusp widths and comparing them with Eq. (3) the assumption is implicit that these peaks tend asymptotically to zero in their tails. Hence, if there is a background contribution to the measured peaks and this contribution is included when determining peak heights, the resulting peak widths at half maximum (or any fraction of the total peak height) will be too large because they are measured with too low a level applied to the "real peak." This also explains the drastic increase of Δv_b seen in Fig. 3(a) at lower v_i where the background contribution becomes large relative to the peak height. Steckelmacher *et al.*[10] quote a similar increase, that is, a tendency of Δv_b to infinity, in the high-velocity range of their measurements where, apparently, the ETC contribution decreases faster than an underlying background.

We conclude that, when determining beam-foil convoy-electron cusp widths, great care has to be taken in the correct evaluation of peak heights. It is obviously incorrect to measure them from the base line. Is it then correct to subtract a background estimated by joining peak tails? This procedure must be qualified as rather arbitrary. According to the $1/v'$ dependence of the cross section for ETC, peak tails extend to large values of v'; hence, the method of joining these tails may easily lead to an overestimation of a background contribution, We understand that it is difficult to make a quantitative *a priori* estimation of this contribution which will be discussed in more detail, in what follows, when we evaluate our measured electron spectra in terms of a parametric expansion of the cross section for ETC, as it has been used in I for the $H^+ \to$ He system.

We observe in Fig. 4 that the peak heights go through a maximum at $v \simeq 2$ a.u., in fair agreement with a previous discussion of convoy-electron yields.[7] This behavior is similar to that obtained in theoretical calculations of the $H^+ \to H$ total ionization cross section: Shakeshaft,[18] by a coupled state calculation, and Banks *et al.*,[19] by a classical-trajectory Monte Carlo method, predicted that the ECC contribution to this cross section has a steep maximum at 50 keV ($v_i \simeq 1.5$ a.u.), which is reflected on the dependence of the ionization cross section with velocity, as measured by Shah and Gilbody.[20] If we accepted an ETC mechanism for the production of the measured convoy electrons we would, however, have to be careful in interpreting this analogy. As a matter of fact, if in Fig. 9 of Ref. 20 this ECC contribution is subtracted, the difference,

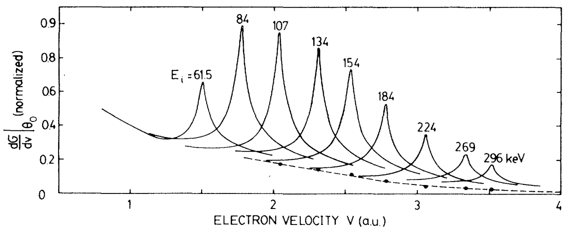

FIG. 4. Set of convoy-electron spectra for $\theta_0=2°$, taken at the specified energies E_i, normalized to the collected ion charge and represented as $d\sigma/dv \mid_{\theta_0}$, defined in Eq. 4. (--●--), background resulting from fitting procedure.

which is representative for a simple ionization process, has a maximum at 90 keV, that is, at 1.9 a.u. on a velocity scale, just about where we find our maximum yield. If we interpret the origin of the electrons contained in our measured peaks as produced by ELC, then in the moving frame they would have been produced by such a simple ionization process, whereas in that frame the contribution from ECC by the target would be localized in the neighborhood of zero velocity and therefore not be comprised by the measured peaks. This procedure would not violate the fact that, as already emphasized, in the case of an atomic target it is not possible to separate ECC- and direct-ionization electrons.

In Figs. 5(a) and 5(b) we represent the skewness r as defined in Eq. (6) as a function of v_i and θ_0, respectively. It is seen that, in spite of the essential discrepancies in widths, when determining r it almost does not matter if the apparent background has been subtracted or not. In contrast to the strongly asymmetric ECC cusps obtained in I for the H^+-He gas system, for which the observed skewnesses were of the order of 3, we note that in the present case of hydrogenic projectiles traversing carbon foils the resulting skewnesses are only slightly larger than 1. Former evidence obtained for heavy-ion beam-foil interactions also shows almost-symmetric peaks which, however, are slightly

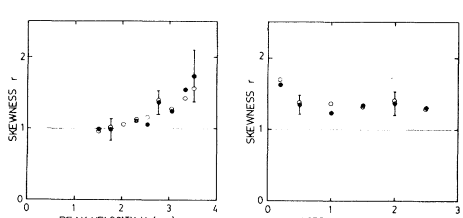

FIG. 5. Skewness r, defined in Eq. (7): (a), plotted as a function of v_p for $\theta_0=2°$; (b), as a function of θ_0 for $v_p=2.78$ a.u. (○), data obtained with apparent background subtracted; (●), with background included.

skewed towards higher electron velocities ($r \lesssim 1$).[15]

We now proceed to perform a more detailed discussion of our results, which allows for a better comparison with the measurements obtained for the proton—He-gas system, by applying a parametrization of the measured electron spectra, as proposed in I. This parametrization, applied to the case of a simple binary collision, was performed in terms of coefficients $B_j^{(n)}$ such that the resultant cross section for ECC was

$$\frac{d\sigma}{d\vec{v}}\frac{1}{\vec{v}}[B_0^{(0)}(v_i)+B_1^{(0)}(v_i)\cos\theta'+v'B_0^{(1)}(v_i)+v'B_1^{(1)}(v_i)\cos\theta'] \ . \quad (9)$$

Here θ' is the angle enclosed by $\vec{v}_i$ and $\vec{v}\,'$, and the $B_j^{(n)}$ depend on the proton velocity v_i. Equation (9) results from a double expansion of the transition amplitude in terms of a power series in v' and Legendre polynomials in $\cos\theta'$. This equation has been derived in I from the transition amplitude for a single ionization process (ECC). It allows for the inclusion of different contributions to the amplitude, including ELC. Its terms are independent of any specific theory and could be interpreted by using a multiple-scattering expansion,[21] a perturbative expansion,[22] or any other acceptable approximation. Furthermore, if we accept the possibility of an alternative or additional process to ETC, this may, in principle, introduce additive contributions to any of the terms in Eq. (9). A comparison with the parametrization that resulted in I for a single-collision process enables us to establish quantitative and physically significant differences that are typical for the beam-foil convoy-electron spectra studied.

By integration over the instrumental resolutions we found in I

$$Q(v)=B_0^{(0)}(v_i)U_0^{(0)}(v)+B_1^{(0)}(v_i)U_1^{(0)}(v)+B_0^{(1)}(v_i)U_0^{(1)}(v)+B_1^{(1)}(v_i)U_1^{(1)}(v) \ . \quad (10)$$

We again use this expression to obtain a least-squares fit of the measured distributions. A typical result is shown in Fig. 6, which furnishes the information equivalent to that contained, for the case of a gas target, in Figs. 6 and 7 of I.

First, we observe that the fitted cusp (Q) agrees well with the measured spectrum. We conclude that, as a matter of fact, the distribution of convoy electrons emerging from a solid target forms a "real cusp" in that it obeys a fitting procedure which is based on a cross section given by Eq. (9), and that this equation contains the factor $1/v'$ that is typical

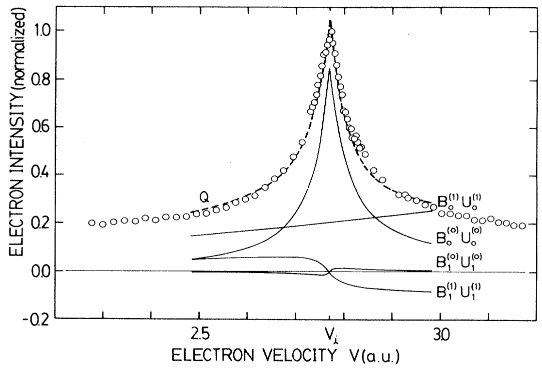

FIG. 6. ETC cusps for $E_i = 192$ keV; $\theta_0 = 1°$: (●), experiment; (---), fitted cusp $Q(v)$ as resulting from Eq. (10); (—), contributions $B_j^{(n)}(v_i)U_j^{(n)}(v)$ to the fitted cusp, as specified.

for an ETC process. We remark that in Ref. 9 it had been questioned whether beam-foil convoy electrons are the result of an ETC process that leads to a diverging $d\sigma/dv$.

Also shown in Fig. 6 are the individual contributions from each term in Eq. (8). We proceed to compare them with the corresponding contributions that, for the H^+-He system, are shown in Fig. 7 of I.

The term $B_0^{(0)}U_0^{(0)}$ represents the cusp that results in Eq. (9) from the simplified cross section $B_0^{(0)}(v_i)/v'$ given by Dettmann *et al.*[7] for the ECC process, or obtained by Drepper and Briggs[6] for the ELC process. This cusp is slightly skewed towards higher electron velocities because the resolution volume of the spectrometer increases with increasing v.

Contrary to what has been observed in I for a gas target, the term $B_1^{(0)}U_1^{(0)}$, which stems from the diverging asymmetry term in Eq. (9), can be neglected when experimental and fitting errors are considered. This is related to the nearly symmetric beam-foil convoy-electron peaks measured and leads us to think in favor of the dominance of an electron-loss process (ELC) for which, as has been verified for heavy ions as well as in our laboratory for He^+ incident on H_2 (see Figs. 1 and 19 of Ref. 4), symmetric peaks are also observed in gas targets.

For the second asymmetric term $B_1^{(1)}U_1^{(1)}$ which, according to Eq. (9), is related to asymmetries that are important in the peak tails, we found the same order of magnitude and sign for the solid target as was observed in I for protons interacting with a He-gas target. The slight negative skewness of our measured cusps stems from this term, and may be attributed to the increase of an underlying electron emission with decreasing velocity, which is clearly seen in Fig. 4. For the case of (heavy) ions with large velocities this electron emission is very small and practically velocity independent such that the observed positive skewness of beam-foil electron cusps can be attributed only to the increase of the instrumental resolution volume with increasing v that is always present and characteristic for any measuring equipment plus an eventual positive contribution from the term $B_1^{(0)}U_1^{(0)}$.

Finally, we notice that the term $B_0^{(1)}U_0^{(1)}$, which is characteristic for an additive background contribution to the peak at $v = v_i$, becomes 20 times larger for the case of the present beam-foil interaction than it was in I for a He-gas target for which the contribution from this term could be considered negligible. As a consequence, we conclude that the main contribution to this large background is due to an independent secondary-electron emission process, which appears for solid targets.

For ion velocities $v_i > 2$ a.u., for which our fitting procedure worked well, we include in Fig. 4 the values of $B_0^{(1)}U_0^{(1)}$, related to the measured peak heights and considered at each $v = v_p$ as the background of the corresponding peaks. It is clearly seen that this background contribution, as it results from our fitting procedure, is sensibly lower than that suggested by the procedure of joining peak tails. It is, however, also obvious that it cannot be ignored.

CONCLUSIONS

Our study of the shape of beam-foil convoy-electron cusps, which was performed with the $H^+ \rightarrow C$ system at proton velocities between 1.5 and 3.5 a.u. and compared with previous measurements of others as well as with our own former results of single-collision convoy-electron production in the $H^+ \rightarrow He$ system (I), leads us to the following conclusions.

The measured spectra can be fitted with an expansion of the cross section that contains the divergent factor $1/v'$ which stems from the Coulomb attraction electron projectile and is essential for an ETC description. On the other hand, our fitting procedure shows a large contribution which has a smooth behavior for electron velocities near to the peak and was not observed in I for the case of a gas target. This indicates that for solid targets there is an alternative process which should be added to ETC. This additional contribution may be considered as background and attributed to an independent secondary-electron emission process.

We note that this background is sensibly smaller than an apparent background as it results from the usual method of joining peak tails. We confirm that when this apparent background is subtracted from the measured peaks, the FWHM result, in accordance with previous evidence,[9] independent of v_i and also of θ_0. On the other hand, if a background contribution is ignored and peak heights are measured from the base line,[10] the resulting FWHM follow, in the range of the higher projectile velocities covered in the present measurements, an approximately linear dependence on $v_i\theta_0$. However, these widths are larger than the simple theoretical prediction given by Eq. (3). Contrarily, in the range of smaller velocities where the above-mentioned secondary-electron emission process dominates over ETC, the FWHM become very large if peak heights are taken from the base line. We conclude that both methods of evaluating peak widths are of dubious value.

Undoubtedly, the shapes of the experimental cusps and their discussion as regards our fitting procedure indicate the Coulombic divergence of the scattering amplitude when $v' \rightarrow 0$, which is typical for a genuine ETC process. Whether this corresponds to ECC or ELC is a more subtle problem. We believe that differences between these two processes should be reflected in the asymmetry of the peak. Corrections to the first-order ECC amplitude which are proportional to $v'^{-1}P_1(\cos\theta')$ come from high-order perturbation terms. On the other hand, the first-order approximation for the ELC amplitude leads to an anisotropy which is proportional to $v'^{-1}P_2(\cos\theta')$ (Ref. 23); experimentally it is almost unobservable.[4] We also find that the peaks measured in the present experiment are almost symmetric, in accordance with the small value of the $B_1^{(0)}$ coefficient obtained when our spectra are fitted by Eq. (10). This indicates that the process of beam-foil convoy-electron production should be an ELC, rather than ECC, effect.

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