ELECTRON "CUSP" SPECTROSCOPY OF THE FORWARD PEAK IN CONTINUUM ELECTRON CAPTURE AND LOSS IN GASES AND SOLIDS*

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Résumé. Nous discutons les résultats de plusieurs récentes expériences de collision ion-atome et ion-solide en ce qui concerne le pic en avant dans la production d'électrons du continu à partir de la capture et la perte de l'électron vers les états du continu centrés sur le projectile. L'accent est mis sur la discussion de trois expériences récentes effectuées sur les accélérateurs tandem de ORNL et BNL. La première a trait au désaccord entre la théorie et l'expérience à propos de la dépendance en Z du projectile pour la capture de l'électron vers les états du continu centrés sur le projectile (ECC) dans les collisions ion-atome. La seconde concerne la découverte d'une structure périodique non-prédite (interférence?) dans la voie de la perte de l'électron (ELC) dans les collisions ion-atome. La troisième concerne l'impuissance des modèles ECC et "wake riding" à reproduire les caractéristiques du pic en avant dans les collisions ion-solide.

Abstract. Results of several recent ion-atom and ion-solid collision experiments concerning the forward peak in continuum electron production from electron capture and loss to projectile-centered continuum states are discussed. Emphasis is given to discussion of three recent experiments carried out at the ORNL and BNL tandem accelerators. The first concerns disagreement between theory and experiment on the projectile Z dependence for electron capture to projectile-centered continuum states (ECC) in ion-atom collisions. The second concerns the discovery of unpredicted periodic (interference?) structure in the electron loss channel (ELC) in ion-atom collisions. The third concerns failure of both ECC and "wake-riding" models of the forward peak characteristics in ion-solid collisions.

INTRODUCTION

Since the pioneering experimental work of Crooks and Rudd [1] and the associated theoretical work of Macek [2] (anticipated in part by Oldham [3]) on electron "cusps" from electron capture to continuum states (ECC) for fast protons on He, much theoretical [2-9] and experimental [5,10-25] attention has been devoted to electron ejection from target atoms into such projectile-centered continuum states. The characteristic cusp-shaped peak in the ejected-electron velocity distribution, which is sharply peaked near the projectile velocity, and also sharply peaked in the forward direction, was identified at nearly the same time for light ions passing thru C foils by Harrison and Lucas [10]. These authors have continued such work with other collaborators in a series of investigations [5,11,19,20] for various H, He projectiles, mostly in thin solid and occasionally in gaseous targets, at projectile energies up to 1.2 MeV/A. Extensive work with both solid and gas targets and H, He projectiles has also been un-

dertaken by Menendez, Duncan and co-workers [12-17], and with solid targets by Meckbach *et al.* [17]. The latter authors have written an excellent summary article [17], whose title "Do present 'charge transfer to the continuum' theories correctly describe the production of $v_e = v_i$ in ion beam-foil collisions?" emphasizes several controversial disagreements between the various data and theoretical predictions.

Chiu, McGowan, and Mitchell [18] have extended the work of Meckbach *et al.* [17] to gas targets, and find support for an ECC description in gas targets, in opposition to alleged deficiencies of such a description for solid targets [17]. But recently Steckelmacher *et al.* have criticized the interpretation given the data of Meckbach *et al.* [17] on instrumental resolution and background treatment grounds, and argue for the validity of the ECC model for the solid target case as well, and against the rival, solid-state "wake-riding" description [8,9]. The latter model considers the possibility that electrons may be trapped in an oscillatory, electron density fluctuation polarization potential extending behind and moving with the projectile, finally being liberated at the exit surface.

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MASTER

As we shall see, in the work of our laboratory, which is distinct from all previous work by virtue of the use of faster, heavier, bare and highly ionized ions (permitting wide projectile charge state variation), we find agreement with neither the ECC nor "wake-riding" models for the solid target case [25].

The work of our laboratory concerning the forward peak was not originally motivated so much by intrinsic interest in properties of the forward peak as by a fascinating assertion of Bottcher concerning the mechanism of many-electron stripping of target atoms by higher Z, bare projectiles in single ion-atom collisions [26]. His paper proposes to explain events like the simultaneous 10-electron excitation of Ne by bare Ar ions which we observed in our laboratory five years ago [27] by appealing to multiple electron capture to the projectile-centered continuum as the dominant mechanism.

Whether his assertion is valid remains an as yet experimentally unsettled question. But all three of our initial experiments devoted to this question have led both to unanticipated discoveries and to significant differences with theoretical descriptions of the forward peak. These three experiments - to be discussed at some length - are very much a group effort with my colleagues Vane, Suter, Laubert, Elston, Alton, Griffin, and Thoe, ably aided by the ORNL and BNL tandem accelerator laboratory staffs. The extensive work of Vane in his painstaking design, construction, assembly, testing and modification of all of the apparatus excepting an electron energy analyzer kindly lent us by H.O. Krause of ORNL deserves special mention, as do the efforts of Suter to understand the periodic (interference?) structures we have recently discovered in the wings of the forward peak in electron loss to continuum (ELC) processes [24], of Laubert who has led the solid target work [25], and Elston and Thoe whose unsung development of the electronic control and computer-based data acquisition systems used in our work has been indispensable. Because all three of the experiments [25,26,27] have led to both new discoveries and challenges to theory, and because many excellent reviews of the complementary work with H, He projectiles are available, e.g. [5,9,17,20], my discussion will focus on these previously unreviewed, complementary results with heavier and highly ionized, faster projectiles.

A key feature of our experimental procedure is the easy interchange of short gas and thin solid targets at the same physical position with all aperture sizes, dimensions, positions, and other experimental details unaltered. It has therefore been possible to cancel most systematic apparatus effects in comparing gas and solid target results to first order. By using single ion-atom collision techniques, by using bare and few-electron ions of appreciably higher charge than heretofore, by extending the velocity range of measurement appreciably above that of earlier experiments, and by studying charge-state variation over an appreciably wider range than used previously, we have thus been able to test experimentally features of continuum electron-capture and -loss theories which have been inaccessible in previous experiments. These somewhat orthogonal tests complement rather than duplicate earlier experimental tests, but, like them, raise new questions about still other conspicuous disagreements.

Before proceeding with a detailed discussion of methods used and results obtained in the three experiments, a few additional comments concerning disagreements between theory and experiment and among experimental results seem worth making. Notable among these disagreements are the following: For sufficiently large ion velocity (V_i) and small projectile rest-frame electron velocity $|\vec{V}_e - \vec{V}_i|$, Dettmann, Harrison, and Lucas [5] obtained the differential cross-section for ECC in the form $d\sigma/d\vec{V}_e = F(V_i)f(|\vec{V}_e - \vec{V}_i|)$. Heckbach *et al.* [17] claim that a vector function of $(\vec{V}_e - \vec{V}_i)$ is needed to explain their cusp-shape results for protons on C targets, when longitudinal ($\hat{z}$) and transverse components ($\hat{\theta}$) of $\vec{V}_e - \vec{V}_i$ are separately scanned, and assert a true cusp is not observed (i.e. their results support the view that $f(\vec{V}_e - \vec{V}_i)$ remains finite as $\vec{V}_e \rightarrow \vec{V}_i$ instead of taking the form $|\vec{V}_e - \vec{V}_i|^{-1}$). Also, the predicted dependence of cusp width on beam velocity was not observed, a discrepancy corroborated in the independent measurements of Menendez and co-workers [12-16]. On the other hand, Cranage and Lucas [11] find excellent agreement with theoretical cusp shapes for longitudinal (electron energy) scans, provided a large direct ionization background is first subtracted. We have confirmed the shape results of Cranage and Lucas for 0.7-MeV/A d^{10+} on Ar collisions, and have further demonstrated Z independence of the

FIG. 1. - Schematic diagram of the forward peak electron spectrometric apparatus. (1) 0.71 mm aperture; (2) 0.33 mm aperture; (3) 4 mm long gas cell, 2 mm exit aperture; (4), (5) Inner, outer spherical sector plates; (6) 0.7 mm exit aperture; (7) Negative biased electron multiplier cone; (8) 7.9 mm Faraday cup shielding aperture; (9) Bias ring for adjacent Faraday cup; (11) Analyzer housing; (12) Variable entrance aperture; (13) Electron multiplier output.

corresponding to 0.7 - 5 MeV/A. All beams are collimated to 1/3 mm diam and $\pm 0.025^\circ$ angular spread, and then traverse a 4-mm-thick target cell terminated by ~2-mm apertures (or a foil target centered at the same location). The beam and accompanying electrons then enter along the central ray of a 180° spherical-sector analyzer of mean radius 3.8 cm, whose $\Delta E/E$ of 1.4% full width at half-maximum is set by a 0.71-mm analyzer exit aperture, and the source dimensions at the center of the cell. The minimally deflected ion beam passes through an aperture in the larger-radius plate of the analyzer and into a Faraday cup used for beam normalization. Typical gas pressures of ~15 mTorr are established by a standard feedback-controlled capacitance-manometer system. Single-collision conditions and negligible charge changing are established by extremely linear plots of integrated cusp cross sections versus pressure for the various ions and energies. The plot intercepts typically coincide precisely with very small residual cusp cross sections measured at zero pressure. Spurious signals from electron loss by contaminant beams were ruled out, as deliberate changes in the accelerator vacuum by a decade in pressure produced no noticeable effect on pressure linearity. The fine collimation guarantees that the beam never encounters any aperture or surface in the gas cell or spectrometer regions, as verified by very low spurious signals obtained at zero pressure. Magnetic fields

are reduced to $< 3 \times 10^{-6}$ T over the spectrometer volume by three orthogonal external coils. Changes in coil current of $\leq 20\%$ produce negligible changes in cusp shape and integrated production cross sections.

A sample electron-energy cusp obtained for O^{8+} traversing Ar at 30 MeV is shown in the inset to Fig. 2, and for 40 MeV O^{8+} in the upper left corner of Fig. 3. Our exploitation of an improved signal-to-background ratio over that of Cranage and Lucas [11] revealed rich structure in the cusp wings for O^{6+} (but not for O^{8+}), as depicted in Fig. 3, and as will be discussed in a subsequent section.

FIG. 2. - Z and V_i dependence of electron capture into continuum states for bare C^{6+} and O^{8+} ions in Ar are shown in the upper portion, in a $\log \sigma$ versus $\log E/A$ power-law plot. The lower portion shows charge-state variation data on integrated cross sections for $O^{6+} - O^{8+}$ at 30 MeV. The inset shows a cusp for O^{8+} ions in Ar at 30 MeV, and has superposed on it a d -Ar calibration cusp (only a representative small fraction of data points over the peak are shown).

It is of interest to note a very useful feature of such fast electron cusp spectroscopy. The kinematic transformation between projectile and laboratory frames results in a non-linear but high gain amplification of small energy intervals very near zero energy in the projectile rest frame. For example, the 0 to 100 meV electron kinetic energy interval in the rest frame of a 5 MeV/A projectile is transformed into the interval 2743 eV - 2776 eV for zero degree electrons in the laboratory frames for

cusplike shape. But we are puzzled to find much smaller direct-ionization-background subtractions than those of Cranage and Lucas.

Very recently Steckelmacher *et al.* [20] have challenged the interpretation of the observed V_i independence of longitudinal and angular (transverse velocity) cusplike widths observed by Meckbach *et al.* [17] and Chiu *et al.* [18] for solid C targets. This independence had been used [17,18] in inferring a possible vectorial functional dependence in $f(\vec{V}_e - \vec{V}_i)$, as opposed to $f(|\vec{V}_e - \vec{V}_i|)$. All authors seem to agree that in the ion-atom collision case corresponding cusplike widths do scale in proportion to V_i , as predicted theoretically [5]. The challenge is based on estimated, large peak height corrections brought about by saturation effects stemming from finite analyzer resolution very near the cusp, and on an allegedly improper background subtraction prior to cusplike width estimation.

The question of whether and how to subtract backgrounds underneath the cusps is fundamental. A convincing argument has been made by Rudd and Macek [28] and subsequently by many others that no unambiguous background subtraction of direct, target-centered ionization electrons from those due to projectile-centered ECC processes can be made. Essentially one argues that electrons reaching particular energy-momentum continuum states are physically indistinguishable, and that which mechanism operates to produce a specific electron cannot be decided even in principle. In supporting the ECC model for the solid target case, Steckelmacher *et al.* [20] seem thus to make a somewhat valid criticism of the peak width estimation procedure of Meckbach *et al.* [17] (although a co-author of [20], Lucas [11], seems to have made similar background subtractions from time to time [11]).

The first of the three experiments I shall discuss in detail [23] is in disagreement with two different classes of theories [2,6] vs. [3,5] concerning the projectile Z dependence of ECC. The second [24] concerns our discovery of interesting, periodic (interference?) structure in the wings of the forward peak in the ELC channel. The third [25] concerns the failure of both ECC and solid-state "wake-riding" models [8,9] to describe our solid target results.

SUGGESTED CONNECTIONS BETWEEN ECC, ELC CAPTURE TO HIGH RYDBERG STATES, RADIATIVE RECOMBINATION, AND THE BEAM-FOIL CASCADE PROBLEM

The presence of an abundance of electrons accompanying a projectile emergent from a solid target at nearly the same speed and in nearly the same direction leads one to speculate concerning the possible contribution of such electrons to long-lived cascades by means of radiative recombination processes from continuum states. Indeed, capture to high Rydberg states has received much discussion in this and previous conferences in this series. Several years ago Rudd and Macek [28] had already emphasized the close connection between excitation to or capture into a band of high Rydberg states characterized by Δn , and similar continuum bands above the ionization limit. As they point out, ejection of slow, secondary electrons is a natural continuation of excitation to states of high principal quantum numbers, and that the electron capture process should continue beyond the ionization limit of the hydrogen atom in a smooth, continuous, and uninterrupted way. In their model, the differential cross section for producing electrons with low energies in the rest frame of the projectile contains a component given by $d\sigma'/dE' = \bar{\sigma}'_{ex}(E')$, where E' is the electron energy in the projectile frame, and $\bar{\sigma}'_{ex}(E')$ is a slowly varying function of E' . The constant $\bar{\sigma}'_{ex}(E')$ near $E' \approx 0$ is connected with the constant $\bar{\sigma}_{ex}$ in the $1/n^3$ law for electron capture reaction according to $\sigma_n(ex) = \bar{\sigma}_{ex} \Delta n/n^3 = \bar{\sigma}_{ex} \Delta E_n \approx \bar{\sigma}'_{ex}(E') \Delta E'$. The replacement of $\Delta n/n^3$ by ΔE_n is specific to the Coulomb potential, and accounts for the smooth transition right across the ionization limit.

In recent years many laboratories including our own have carried out studies of radiative recombination through radiative electron capture by fast projectiles, primarily in the X-ray region. Generally the discussion of such experiments has centered on capture from bound states of a target atom. Because the mechanism of forward peak electron production is so poorly understood, particularly for solid targets, I would like to suggest that the possible role of radiative capture of electrons in the forward peak in radiative recombination be examined both theoretically and experimentally as it relates to the beam-foil cascade problem in the very near future.

EXPERIMENTAL METHOD

A schematic diagram of the apparatus is displayed in Fig. 1. Projectile ions from the ORNL or BNL tandem accelerator traverse a thin gas or interchangeable solid target over a velocity range

FIG. 3. - Normalized spectra for electron capture and loss to continuum states in the forward direction for 2.5-MeV/amu O^{9+} and Si^{9+} on Ar. Zero-count base lines are shown for each spectrum. Statistical errors are about 2% at the peaks. The "difference" spectrum in the lower left-hand portion of the figure results from direct subtraction of the O^{5+} from the O^{4+} normalized data.

an overall energy interval amplification factor of ~ 330 . The additional advantage of coping with detection problems for 3 keV electrons rather than 0.1 eV electrons can scarcely be overestimated. The compression of the 4π solid angle in the projectile frame into a small cone very near the forward direction can also represent a considerable advantage in collecting power for all the electrons of interest in some desired energy interval. The corresponding drawbacks are, of course, extremely coarse angular resolution (in the projectile frame), and the peak shape and height distortion discussed by Steckelmacher *et al.* [20] resulting from the effects of finite analyzer energy resolution for very small angular intervals near the forward direction. Nonetheless, the inherent high gain energy interval amplification is a most promising experimental tool which remains to be exploited.

RESULTS CONCERNING ANOMALOUS PROJECTILE Z DEPENDENCE

A significant prediction of the theory of Dettmann, Harrison, and Lucas [5] and also that of Macek [2] is a Z^3 dependence for $d\sigma/dv_e$ for given V_i . We did not find this dependence in the observed cross-section ratio (when integrated between suitably scaled, fixed, velocity limits) for bare O^{6+} vs C^{6+} ions traversing Ar gas at the same velocity [27]. But this ratio is independent of velocity,

just as predicted. To see where the predicted Z^3 dependence arises, we can parametrize our results in terms of the simple analytic forms given by Dettmann *et al.* [5]. Highly similar results for cusp shapes and doubly differential cross sections are obtained in the various ECC theories, which differ mainly in the possible occurrence of interference structure as in the formulations of Macek and of Band [2,6]. The theories of Macek and Band add separate first-order amplitudes for direct ionization and charge transfer, leading in principle to interference, which has been sought but not found in 0.5-MeV/A He^{++} -He collisions by Menendez and co-workers [15]. The theory of Dettmann, Harrison, and Lucas [5], which is a second-Born-approximation calculation of the charge transfer to the continuum, leads to a cusp in cross section such that

$$d\sigma(\theta_0)/dv_e = F(V_i) 4\pi^2 V_B Z [(V_e - V_i)^2 + V_i^2 \theta_0^2]^{1/2} - |V_e - V_i|,$$

where in second Born approximation

$$F(V_i) = (2^{16}/10\pi^2) (Z^2 Z_T^{5/2}/V_B^3) (V_B/V_i)^{1/2} (0.3\pi\alpha_B^2).$$

Here V_e , V_i , V_B , Z , Z_T , α_B and θ_0 refer, respectively, to laboratory electron, ion, Bohr velocities, projectile and target atomic numbers, the Bohr radius, and the half-angle of a small cone θ_0 over which the doubly differential cross section is integrated to obtain $d\sigma/dv_e$. Of course $F(V_i)$ can be calculated in other approximations, many of which would be expected to scale like Z^2 . Hence the overall Z^3 factor arises from the linear Z dependence of the forefactor multiplying any form for F which scales as Z^2 .

In the upper portion of Fig. 2 the cusp cross section (arbitrary scale) integrated over electron velocity between fixed but scaled velocity limits to be described is plotted for bare C^{6+} and O^{6+} ions versus energy per nucleon, on a $\log \sigma$ vs. $\log E/A$ plot. The parallelism of the curves shown and their ratio depict both a common velocity dependence, and a velocity-independent Z dependence. Integrating $d\sigma(\theta_0)/dv_e$ between the velocity limits $(1-\alpha)V_i$ and $(1+\alpha)V_i$, where α is arbitrary but consistently chosen to be 0.04, standardizes a fixed, scaled, velocity-interval region of integration, which scales as theoretically predicted by Dettmann, Harrison, and Lucas [5], and minimizes background and shape corrections. Directly measured O^{6+}/C^{6+} ratios at 1.88 and 2.50 MeV/A are approximately

1.87 ± 0.08 and 1.94 ± 0.08 , corresponding to predicted ratios of 2.37 if a Z^3 dependence is assumed. The error bars correspond to range errors in measured ratios. Evidently there is reasonably good agreement between theory and experiment concerning cusp shape, but unacceptably poor agreement concerning Z dependence.

Following the suggestions of Macek (private communication) that the integration limits might be too broad, opening the possibility of a mixed Z -power in the range $Z=6$ to 8, we varied the region of integration, but find no systematic change in the power over the entire range $\alpha = 0.01$ to 0.04. We have also carried out as yet unpublished measurements for couterons and bare Si^{14+} ions in Ar at the same velocities. The same $Z^{2.2 \pm 0.2}$ power law is found to correctly predict both the $d+\text{Ar}$ and $\text{Si}^{14+} + \text{Ar}$ cross-sections, within error bars. The disagreement between theory and experiment thus persists, and either constitutes a fundamental challenge to theory or to experimenters to find something wrong with the interpretation of the data.

RESULTS CONCERNING OBSERVATION OF PERIODIC (INTERFERENCE?) STRUCTURE IN THE FORWARD PEAK FROM FAST PROJECTILE ELECTRON LOSS (ELC)

Drepper and Briggs [7] have given a theory concerning binary-collisional electron loss by fast projectile ions in which the laboratory-frame distribution of the large forward ejected-electron peak displays a very similar cusp in both energy and angle, centered in velocity near $\vec{V}_e = \vec{V}_{\text{ion}}$. The theoretical cusp shape closely resembles that predicted in the ECC theories [2,4,5,6] for bare ions. The theories of Macek and Band [2,6] regarding ECC differ in principle from the other ECC theories in the possible occurrence of interference structure modifying the shape of the observed cusp in electron energy. This structure results from interference of separate amplitudes for direct ionization and for charge transfer to the projectile-centered continuum. While the latter theories are first-order approximations which obtain separate amplitudes for the ionization and charge-transfer contributions, the former theories employ a single amplitude equal to the second Born amplitude away from the forward peak, but exhibiting an enhancement near $\vec{V}_e = \vec{V}_{\text{ion}}$ arising from the use of suitable Coulomb wave functions centered on the projectile. Thus the latter ECC theories admit possible interference effects which are most

pronounced when the phase of the exchange cross section is varying most rapidly because of Coulomb distortion of the final-state wave function. The former single-amplitude theories, of course, lead to no such interference effects.

To our knowledge, prior to our paper [24] there had been no previous discussion of possible interference effects in electron-loss processes, or of possible interference between capture and loss processes leading to the same sort of projectile-centered continuum states. Similarly there had been no previous experimental observation of interference effects in either the ECC or the electron-loss-to-continuum (ELC) channels. An unsuccessful search for ECC interference structure in 0.5-MeV/A H^{++} -He collisions was, however, made by Duncan *et al.* [15]. Within error limits, our more recent experiments on ECC for 1.6-3.9-MeV/A C, O, and Si bare ions traversing He, Ne, and Ar do not exhibit interference structure. Menendez *et al.* [14] have also performed the prototype charge-state-variation experiment, in comparing electron spectra for He^+ and He^{++} on Ar, finding no significant differences in the cusp shapes. However, in experiments with H^- projectiles [7] they obtained quite different electron spectra near $\vec{V}_e = \vec{V}_i$ and proposed to explain the observed structure as resulting from two additive processes, namely single and double electron loss in the forward direction.

In our paper [24] we reported the observation of pronounced and unexplained oscillatory structure in the wings of the ELC forward peak for 1.6-3.9-MeV/A O^{4+} and $\text{Si}^{10,11,12+}$ ions traversing Ne and Ar gases. These structural features exhibit no observable target-gas dependence and show only very weak dependence, possibly of kinematic origin, on projectile energy in the projectile rest frame. Similar but much weaker structure is observed for some O^{9+} and Si^{9+} projectiles other than those already listed but no detectable oscillatory structure is seen for the bare ions.

Figure 3 shows energy spectra obtained for electrons emitted in the forward direction using an argon gas target and several O^{9+} and Si^{9+} projectile ions. All spectra displayed are for projectiles having the same velocity (2.5 MeV/A). Each of the spectra has been normalized to the same peak height and no analyzer-transmission or detector-efficiency corrections have been made. The uppermost two spectra are for bare O^{8+} and Si^{14+} undergoing pure ECC

and exhibit the typical skewed distribution found previously by us for ECC by bare ions (a quantitative theory of the skewness is not yet available).

A much more symmetric, narrower, and almost structureless cusp is shown for O^{5+} . The absolute yield, defined by numerical integration over a fixed fraction of the cusp, is about 2.2 times greater for O^{5+} than a similarly defined yield for O^{6+} . The fraction of ECC can be estimated assuming an effective ion charge of $Z_{eff} = q$ by scaling the known O^{6+} yield by Z_{eff}^2 . Extension to lower-charge states of the ECC contribution elimination according to this procedure shows that for 1.6-2.5-MeV/A O^{q+} projectiles the ELC yield dominates the ECC contribution when L-electrons are present. For O^{5+} at 2.5 MeV/A on Ar the ELC yield is about 4 times the ECC contribution. Thus the narrower, more symmetric, and therefore significantly different peaks observed for O^{3+} , O^{4+} , and O^{5+} are indicative of ELC processes. We observe a similar qualitative behavior in peak-shape variation for the Si^{9+} charge states where, for $q = 11$, ELC and ECC contributions are comparable.

The spectra for O^{6+} in Figs. 3, 4 show pronounced oscillatory structure in both wings of the cusp. In Fig. 3 this structure has been made

FIG. 4. - Expanded view of the O^{6+} + Ar ELC data included in Fig. 3, with raw data points (statistical errors $\sim$ point size). A fitted, slightly skewed, cusp-shaped fit to the data is also shown, together with an off-set and magnified difference curve at the top of the figure.

virtually obvious by means of subtracting the nearly symmetric and structureless peak-normalized O^{5+} cusp from the O^{6+} cusp. This $O^{6+} - O^{5+}$ "difference" result is shown in the bottom left-hand corner of the figure, with the vertical scale expanded by a factor of 2 for clarity. Well-defined maxima and minima located nearly symmetrically about the cusp center are visible. The first obvious maximum in the "difference" spectrum is separated by ~ 100 eV from the cusp center in the lab frame which corresponds to only ~ 2 eV in the projectile frame, demonstrating the utility of the kind of nonlinear electron-energy interval amplification resulting from purely kinematic considerations discussed above.

By use of projectiles with more than four electrons, for example O^{3+} , the oscillatory structure is obscured or eliminated. Characteristic of these lower-charge states is a narrow central cusp on top of a much broader distribution, as shown in the figure directly above the "difference" spectrum. Similar cusp shapes have been observed for the same projectiles at several beam energies (1.6-3.9 MeV/A) and in all cases the strongest oscillatory structure has been evident for O^{4+} projectiles.

Figure 4 provides a previously unpublished, even more graphic presentation of the same data (statistical error bars $\sim$ point size). Here a fitted cusp-shaped curve has been subtracted from the data in velocity space after multiplying the Dettmann *et al.* [5] quoted above by an additional factor $(V_e/V_i)^P$ to account for the observed asymmetry (P is a parameter of the fit). The difference spectrum, off-set and enhanced by an arbitrary factor, is shown at the top of the figure. A pleasing, symmetric difference spectrum is seen, strongly suggestive of an interference pattern. The observed structural features have widths comparable to the finite resolution (1.4% full width at half-maximum) of the analyzer alone, indicating that these features may have widths which are considerably narrower, even in the laboratory frame.

Measurements for the same projectiles (O^{4+} and Si^{9+}) and beam energies but with a different target gas, neon, result in spectra having structural features of different amplitude but occurring at the same energies as those for argon, demonstrating a target independence of the basic phenomenon.

Data obtained under precisely the same experimental conditions with Si^{9+} projectiles are displayed in the right-hand column of Fig. 3. Oscillatory structure in the wings similar to that for O^{6+}

is evident. In contrast to the O data where strong oscillatory structure is found only for the four-electron projectile, the Si data clearly show such strong structure for projectiles with 2, 3, and 4 electrons. For Si^{9+} with $q < 10$ (as for O^{3+}) no clear oscillations have been observed. As in the O^{9+} data, the energy positions of the structural features in the projectile rest frame are approximately independent of q , V_i , and target gas but the energy separations of what appear to be maxima and minima corresponding to those of the O^{3+} spectra are differently spaced.

The wide range of charge states used for Si^{q+} on Ar ($q = 5-14$) gives rise to a monotonically decreasing ELC integrated cusp cross-section ($\alpha=0.04$) with q , producing a factor of ~ 10 drop in going from $q = 5$ to $q = 11$. These yields have been found to be weakly dependent on V_i , verifying for the first time the very recent prediction of Briggs and Drepper [7] that in the present velocity range and higher, such electron-loss cross sections should tend to complete velocity independence. Significant departures (e.g. a factor of ≥ 2 over the range 2.5-3.9 MeV/A) from this weak velocity dependence set in only for $q \geq 11$, just in the range where the ELC cross sections are dropping below the more strongly velocity-dependent [23] ECC cross sections.

Variation of the available experimental parameters (Z , q , V_i , Z_p) has lead to several conclusions: (1) The "positions" of structural maxima and minima in projectile-rest-frame energy are independent of target gas. Thus the effect is projectile specific and therefore cannot be described by a molecular model as are some oscillatory phenomena obtained in ion-atom collisions. (2) The structural "positions" in the projectile frame are approximately independent of both q and V_i , but the amplitudes of the features are strongly dependent on q for O^{9+} (less so for Si^{9+}) and weakly dependent on V_i . (3) The "positions" are dependent on Z_i . (4) The structure found corresponds to electrons having energies between 2 and 20 eV in the projectile frame. Since no single-electron excitation of the highly ionized projectiles can lead to autoionization in this energy range, it is unlikely that the structure results from projectile autoionization.

While a much needed theoretical interpretation of the highly reproducible (observed in hundreds of spectra) structure is admittedly lacking at this time, some possible interpretations can be envisioned. The observed oscillatory structure has

periodicity, especially obvious in the far wings of the $\text{Si}^{10,11,12+}$ cusps, indicative of an interference-based phenomenon. Such structure might be the result of interference between different one-electron transition channels in ELC or interference of amplitudes for multiple-electron ejection in a single-step process. One can also speculate about multiple-electron transitions in ELC leading to the observed structure variations. Structure due to one ELC process might easily wash out that due to another and yield the observed nonoscillatory structure for O^{3+} . It is also possible that multiple-electron loss processes might lead through correlated mutual Coulomb repulsion during ejection to structure similar to that observed for O^{3+} and Si^{9+} (with $q \leq 10$). Though one could also envision the possible interference of single-electron ELC and ECC for values of q where ELC and ECC contributions to the total cross section are comparable, one should bear in mind that the strong structure for O^{3+} ELC is observed under conditions where ELC dominates ECC by a factor ~ 20 .

RESULTS CONCERNING RIVAL ECC AND "WAKE-RIDING" MODELS FOR COLLISIONS IN SOLIDS

As remarked earlier, the ease of interchange of gas and solid targets in our apparatus while leaving all other geometrical and kinematic conditions fixed has permitted us to compare gas and solid target results under conditions where most systematic apparatus effects cancel to first order. A key parameter for comparison of theory and experiment is the full width at half maximum $\Gamma_{l,v}$ of the longitudinal electron velocity distribution of the electrons emerging in the forward direction. In ECC theory [5] $\Gamma_{l,v}$ can be expressed as $\Gamma_{l,v} = \frac{3}{2} V_i \theta_0$, where V_i is the projectile velocity in a.u. and θ_0 half of the acceptance angle, in radians, of the electron velocity analyzer. For gaseous targets experimental results are generally consistent with this prediction, as noted earlier. As discussed in the introduction, some authors [17,18] observe Γ 's that are essentially independent of the velocity of the projectile. These results are at odds with the ECC prediction and the assumption that the "last target layer" is the source of the continuum electrons. The properties of continuum electrons coming from wake riding (WR) states are predicted to be significantly different from ECC electrons. The FWHM of the longitudinal velocity distribution for wake riding electrons can be expressed [8,9], in a.u., as

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

where ω_{Res} is the material specific plasma resonance frequency, $B = Z_i^{eff} C_\eta$ where Z_i^{eff} is the effective charge of the ion in the medium, $C = \exp(-3\pi\gamma/4\omega_{Res})$ accounts for the damping of the wake through γ (the width of the plasma frequency distribution), and $\eta = 1-2$ is determined by a correlation between the wake and the wake bound electrons. In the wake riding description of such 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 the ECC prediction. Our experiment [25] was designed to test these specific predictions by using various targets (C, Al, Ag, and Au), and large atomic numbers for the incident ions ($Z_i = 1$ to 28) at high projectile velocities (6 to 14 a.u.). These experimental conditions are favorable to wake formation during passage of the ion through the solid. Previous experiments with solid targets (see Bibliography) were performed at lower projectile velocities (1-3 a.u.) where it may be questionable if a wake is formed [8,9]. We find that there are distinct differences between solid and gaseous targets in agreement with other experiments, but none of the predictions of the wake-riding theory concerning the width of the longitudinal velocity distribution of convoy electrons are borne out.

Ion beams (H_i^+ , $E_i = 2.5$ to 3.86 MeV/A; O^{+q} , $E_i = 1$ to 3.86 MeV/A; Si^{+q} , $E_i = 1$ to 4.7 MeV/A; and Ni^{+q} , $E_i = 1$ to 2.5 MeV/A of ~ 20 pA intensity and various charge states were passed through thin C, Al, Ag, and Au targets.

Typical data in Fig. 5 show the longitudinal electron velocity distribution, $d\sigma/dv_e$ (corrected for the variation in the energy acceptance band $\Delta E_e C E_e$) for 108 MeV Si^{+9} incident on a 100 $\mu\text{g}/\text{cm}^2$ Au foil (solid line), and the normalized velocity distribution (normalization constant ~ 3) for 108 MeV Si^{+13} traversing 30 mTorr of Ar. The dashed vertical line marks the velocity of the incident projectile. The velocity distribution observed from a solid target was found to be independent of the incident silicon charge state q ($q = 6$ to 14), the velocity of the projectile, the target material, and of the thickness of the target. Hence the solid line marks the typical

FIG. 5. - The differential cross section $d\sigma/dv_e$ as a function of the electron velocity, v_e , of continuum electrons emerging near 0° with respect to the ion beam for 108 MeV Si^{+13} on 30 mTorr Ar gas and Si^{+9} on 100 $\mu\text{g}/\text{cm}^2$ Au foil. The electron energy scale appears at the top of the figure.

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, and exhibits a markedly different skewness. This is a completely unexpected result not predicted by either ECC or WR theories and can be indicative of the different processes of excitation for projectiles traversing solids and gases.

Velocity distributions of the kind shown in Fig. 5 were acquired for targets of C ($t=30 \mu\text{g}/\text{cm}^2$), Al ($t=50 \mu\text{g}/\text{cm}^2$), Ag ($t=100 \mu\text{g}/\text{cm}^2$) and Au ($t=100 \mu\text{g}/\text{cm}^2$) with the afore-mentioned ions. These thicknesses were chosen to permit sufficient spatial extent for wake formation and charge equilibrium. 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 ≈ 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. 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 ECC theory and WR theory are shown in Fig. 6. The dashed line through the origin is the result of the ECC theory with an acceptance half angle for the electron energy analyzer of $\theta_0 = 1.3^\circ$. The results for gaseous targets (Ne and Ar) with O^{+8} and Si^{+14} projectiles are indistinguishable within experimental uncertainty ($\pm 10\%$) and follow the predicted ECC linear velocity dependence in the velocity range of 8.7 to 12.4 a.u. The ≈ 25 measurements with gaseous targets and O^{+8} and Si^{+14} projectiles are represented by the three open points in Fig. 6. The light solid lines in Fig. 6 are the result of the WR theory [8,9] for various incident ions, denoted by Z_1 , on an Al target. The material constants, ω_{Res} and constant C, are shown in Table I. For C targets, WR theory predicts values of $\Gamma_{L,v}^{WR}$ that are approximately 2/3 of those for Al. For Ag and Au targets WR theory predicts about equal values of Γ that are approximately 1/3 the Al values. The solid curve marked Ag is obtained from the above expression for $\Gamma_{L,v}^{WR}$ for protons incident on

FIG. 6. - The full width at half maximum of the longitudinal electron velocity distribution, $\Gamma_{L,v}$, in a.u., for continuum electrons as a function of the electron velocity v_e , in a.u. The incident projectile energy, in MeV/A, appears at the top of the figure. The dashed line is the ECC prediction. The solid lines 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 WR theory 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} .

TABLE I

The measured full width at half maximum, $\Gamma_{L,v}$ in a.u. of the longitudinal velocity distribution of continuum electrons in the forward direction from thin solid targets. The energy range, in MeV/A, of the incident ions is indicated below the ionic species in parentheses. The material plasma frequency ω_{Res} , in a.u., and damping constant C, defined in the text, are listed, respectively, in parentheses below the target material. The bottom line lists the mean value of $\Gamma_{L,v}$ for a particular target material.

Ion	Target	C	Al	Ag	Au
		(0.74, 0.16)	(0.57, 0.90)	(0.92, 0.009)	(0.95, 0.009)
1	(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
N	(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

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 ECC theory, and with the Z_1 velocity, and target material dependence of the WR theory as exemplified by $\Gamma_{L,v}^{WR}$. From this we conclude that the majority of continuum electrons from solids do not originate from wake-bound electrons trailing ions in solids.

Thus measurements of the longitudinal velocity distribution of continuum electrons from solids disagree with predictions of both ECC theory and with the WR 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.

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