Z, Velocity, and Charge Dependence of Zero-Degree Electron "Cusps" from Charge Transfer to Continuum States of Bare and Highly Ionized Projectiles

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Data on continuum electron capture and loss for bare and highly ionized C^{q+}, O^{q+} ions traversing Ar at energies 1.6–2.8 MeV/A reveal striking disagreements with corresponding theories. We demonstrate a velocity-independent ($\sim Z^{2.2 \pm 0.2}$) scaling for continuum capture by bare ions, a Z-independent velocity scaling, and an approximately q-independent ($q = 6, 7, 8$) equality of continuum electron-capture and -loss cross sections at velocities corresponding to ~ 2 MeV/A.

Since the pioneering experimental work of Crooks and Rudd and the associated theoretical work of Macek on electron "cusps" from charge transfer to continuum states[1] for fast protons on He, much 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 ions passing through C foils by Harrison and Lucas.[2] These authors have continued such work with other collaborators in a series of investigations[2] for various 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 has also been undertaken by Menendez and co-workers,[3] and with solid targets by Meckbach *et al.*[4] The latter authors have written an excellent summary article,[4] which emphasizes several controversial disagreements between the various data and theoretical predictions which motivated the experiments reported here.

That work with gas targets under single-collision conditions helps disentangle the explicitly solid-state causes of disagreement from those which are intrinsic to binary ion-atom collisions has been well appreciated by Menendez and co-workers,[3] who have pioneered the most extensive work for various projectile, target, and velocity combinations to date. These authors have also performed the prototype charge-state-variation experiment, in comparing shapes and cross sections for He^+, He^{++}, and H^- on Ar cusps at 0.5 MeV/A. They find, however, in agreement with the assertion of Drepper and Briggs,[1] that in their experiment (unlike the present experiment) electron loss from projectiles both mimics and

dominates the continuum capture cusp. Thus the He^+ results are better characterized in terms of electron-loss processes, yielding little information about the Z dependence of the continuum capture process per se.

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 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.

Notable among the disagreements cited in Refs. 2–4 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[1] obtained $d\sigma/d\vec{v}_e = F(v_i) f(|\vec{v}_e - \vec{v}_i|)$. Meckbach *et al.*[4] 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. 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.[3] On the other hand, Cranage and Lucas[2] find excellent agreement with theoretical cusp shapes for longitudinal (electron energy) scans, provided a large direct ionization background is first subtracted. As we shall see, we have confirmed the shape results of Cranage and Lucas for 0.7-MeV/A d^+ on Ar collisions, and have further demon-

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strated Z independence of the cusp shape.[3] But we are puzzled to find much smaller direct-ionization-background subtractions than those of Cranage and Lucas.

Other disagreements occur. Because highly similar results for cusp shapes and doubly differential cross sections are obtained in the various theories, e.g. those of Dettmann, Harrison, and Lucas and Macek,[1] and differ mainly in the possible occurrence of interference structure as in the formulations of Macek and of Band,[1] we shall follow the lead of Cranage and Lucas[2] in parametrizing our results in terms of the simple analytic forms given by Dettmann, Harrison, and Lucas.[1] (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.[3] The theory of Dettman, Harrison, and Lucas,[1] which is a second-Born-approximation calculation of the charge transfer to the continuum, leads to a cusp in cross section such that

$$d\sigma(\theta_0)/dv_e \cong F(v_i)4\pi^2 v_B Z\{[(v_e - v_i)^2 + v_i^2\theta_0^2]^{1/2}$$
$$- |v_e - v_i|\},$$

where

$$F(v_i) = (2^{16}/10\pi^2)(Z^2 Z_T^5/v_B^3)(v_B/v_i)^{12}(0.3\pi a_B^2).$$

Here v_e, v_i, v_B, Z, Z_T, a_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 $d\sigma/dv_e$ (for our apparatus, $\theta_0 \cong 1.85°$). None of the experiments cited in Refs. 1-3 find nearly such a steep dependence on velocity, particularly for Ar, though Cranage and Lucas claim asymptotic approach to this form for $F(v)$, but only following their large background subtraction.

A significant prediction of the theory of Dettmann, Harrison, and Lucas[1] is a Z^3 dependence for $d\sigma/dv_e$ for given v_i. We do *not* find this dependence in the observed cross-section ratio (when integrated between suitably scaled, fixed, velocity limits) for bare O^{8+} vs C^{6+} ions traversing Ar gas at the same velocity. But this ratio *is* independent of velocity, just as predicted.

In the present experiments at higher velocities we find, in common with the experiments cited in Refs. 1-3, a much weaker power-law velocity dependence than in $F(v_i)$, but in the absence of any large background correction, and also find

no appreciable asymptotic trend. While it should be argued that the high-velocity regime demanded by Born calculations has not been reached, the ratio of v_i to the velocity of an Ar M-shell electron of up to nearly 10 coupled with the lack of asymptotic trends in the observed pure power dependence of continuum electron capture does raise the question of a need for more basic modification of existing theory.

In our experiments continuum electron production near the forward direction was studied for C^{4+}, C^{5+}, C^{6+}, and O^{4+} through O^{8+} ions from the ORNL tandem accelerator traversing Ar gas over a velocity range corresponding to 1.6–2.8 MeV/A. All beams were collimated to $\frac{1}{3}$ mm diam and $\pm 0.025°$ angular spread, and then traversed a 4-mm-thick target cell terminated by ~ 2-mm apertures. The beam and accompanying electrons then entered 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 was set by a 0.71-mm analyzer exit aperture, and the source dimensions at the center of the cell. The minimally deflected ion beam passed through an aperture in the larger-radius plate of the analyzer and into a Faraday cup used for beam normalization. Typical Ar pressures of ~ 15 mTorr were established by a standard feedback-controlled capacitance-manometer system. Single-collision conditions and negligible charge changing were established to 30 mTorr by extremely linear plots of integrated cusp cross sections versus pressure for bare C^{6+} and O^{8+} ions at several energies. The plot intercepts coincided 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 guaranteed that the beam could never scrape any aperture or surface in the gas cell or spectrometer regions, as verified by very low spurious signals obtained at zero pressure. Magnetic fields were reduced to $< 3 \times 10^{-6}$ T over the spectrometer volume by three orthogonal external coils. Changes in coil current of $\lesssim 20\%$ produced 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. 1. Our exploitation of an improved signal-to-background ratio over that of Cranage and Lucas[2] revealed structure in the cusp wings
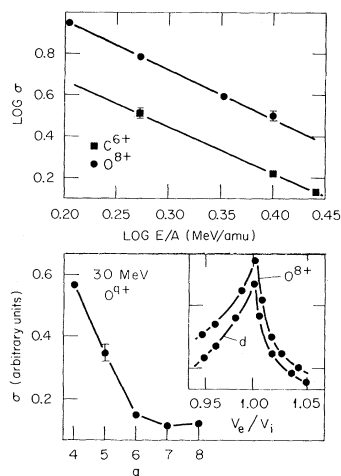
FIG. 1. Z and v dependence of electron capture into continuum states for bare C^{6+} and O^{8+} ions in Ar are shown in the upper portion, in a $\log\sigma$ vs $\log E/A$ power-law plot. The lower portion shows charge-state varia-tion data on integrated cross sections for O^{4+}–O^{8+} at 30 MeV. The 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).

for O^{4+} or O^{5+} (but not for O^{8+}) which is unex-plained and merits further study. Such structure is not evident in our *in situ* $d+$Ar calibration data, also shown in the inset, obtained at 0.7 MeV/A and taken for the purpose of normalization to absolute $p+$Ar cross-sections obtained by Cranage and Lucas.[2] This calibration should per-mit absolute cross sections for continuum cap-ture to be established in a fuller account of our measurements than is possible here, but poses the problem that our cusp-to-background ratios are distinctly higher than that of Cranage and Lucas. We do not agree with their assertion that "it is very difficult to extend the measure-ments to higher energies since it becomes im-possible to separate the cusp from the back-ground. ..."

In the upper portion of Fig. 1 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^{8+} ions versus energy per nucleon, on a $\log\sigma$ vs $\log E/A$ plot. The linearity of these plots depicts a well-defined energy (or velocity) power law; the extent of parallelism and their ratio depict both a common velocity dependence, and a veloc-ity-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 cho-

sen to be 0.04, standardizes a fixed, scaled, velocity-interval region of integration, which scales as theoretically predicted by Dettmann, Harrison, and Lucas,[1] and minimizes background and shape corrections.

The theory of Dettman, Harrison, and Lucas[1] has a predicted Z^3 dependence, and a v_i depen-dence $\sim v_i^{-10}$. Least-squares fits to the experi-mental exponent in v_i^{-n} yield $n = 4.55 \pm 0.19$ and $n = 4.65 \pm 0.14$ for C^{6+} and O^{8+} respectively, where standard errors in the fits are indicated. Direct-ly measured $O^{8+}/C^{6+}\sigma$ 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 concern-ing both velocity and Z dependence. The implied experimental Z dependence of $Z^{2.2 \pm 0.2}$ is weakly dependent on the scaled limits of integration, and can be adjusted accordingly from the present data. Concerning the observed velocity dependence, corrections for variations in channel electron multiplier efficiency have not been applied. It is possible that these corrections would result in an even weaker velocity dependence than quoted here. Acceleration of electrons prior to analysis by $\sim 20\%$ of their laboratory energy led to small de-creases in yield, but the fraction of the observed decrease due to changes in multiplier efficiency has not yet been determined.

A surprise arose in the charge-state measure-ments, e.g. for O^{4+} through O^{8+} ions at 30 MeV. For all but bare ions, the measured cross sec-tion sums the contributions from capture and loss into projectile-centered continuum states, since as pointed out by Drepper and Briggs,[1] very similar cusp-shaped distributions centered near $v_e \cong v_i$ arise from these processes. As shown in the lower portion of Fig. 1, there is remarkably little variation in cross section for charges 6^+, 7^+, and 8^+. Only when projectile L-shell electrons are present do the cross sec-tions appear to rise steeply. This result is sur-prising, as the 6^+ and 7^+ loss cross sections have been measured for O^{q+} in Ar at this beam energy by Macdonald and Martin.[5] They report near equality of O^{6+} total loss and O^{8+} bound-state cap-ture cross sections at this energy, but find a factor of ~ 5 lower 7^+ vs 6^+ loss cross section at this same energy. A systematic study of the cusp cross-section charge-state dependence for both

C^{q+} and O^{q+} vs E/A has been made and will be reported elsewhere.

The present data thus reveal striking disagreement with corresponding Z and v_i dependence features of electron continuum capture theories, and additionally provide charge-state-variation comparisons of total electron-loss cross sections with those for loss processes that populate the ~ zero-degree cusp.

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Photon Statistics and Spectrum of Transmitted Light in Optical Bistability

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A quantum description of the transmitted field is given. In the bistable situation, the stationary Glauber quasi probability distribution has two peaks thereby producing a first-order phase transition. For small incident field the linewidth of the transmitted light is proportional to the atomic density and becomes very narrow as the field approaches some critical value from below. Crossing this value the spectrum splits discontinuously into a triplet (dynamical Stark shift) where the central peak is as high as twice the sidebands.

We have recently studied[1] a mean-field model, which gives the first analytical description of optical bistability[2] (OB) in the purely absorptive case for a homogeneously broadened atomic system. Although this model is quantum mechanical, in Ref. 1 it has been treated only within the semiclassical approximation. The stationary bistable behavior of the transmitted light amplitude E_T obtained by varying the incident light E_I is described by the "state equation"

$$Y = X + 2C_X/(1+X^2), \qquad (1)$$

where

$$Y = \mu E_I/(\hbar^2 \gamma_\perp \gamma_\parallel T)^{1/2},$$

$$X = \mu E_T/(\hbar^2 \gamma_\perp \gamma_\parallel T)^{1/2},$$

$$C = \gamma_0 \rho L \lambda^2/16\pi\gamma_\perp T.$$

μ is the modulus of the dipole moment of the two-level atoms, $\gamma_\parallel = T_1^{-1}$ and $\gamma_\perp = T_2^{-1}$ are the homogeneous atomic relaxation rates, γ_0 is the natural linewidth of the atoms, ρ is the atomic den-