Observation of Oscillatory (Interference?) Structure in the Forward Peak from Fast-Projectile Electron Loss

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Significant unexplained oscillator structure has been observed in the wings of the forward electron-loss peak from 1.6–3.9-MeV/amu O^{q+} and Si^{q+} ions traversing Ne and Ar gases. On the basis of the observed projectile Z_1, q, and velocity and target Z_2 dependencies, this structure appears likely to arise from interference of amplitudes describing alternative channels for populating projectile-centered continuum states, conceivably including channels involving simultaneous ejection of two or more electrons.

Drepper and Briggs[1] have recently published 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 sharp 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 theories of Dettmann, Harrison, and Lucas[2] and of Salin[2] concerning the forward peak in electron capture to continuum states (ECC) by bare ions. The theories of Macek and Band[3] regarding ECC differ in principle from the former 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, there has 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 has been no previous experimental observation of interference effects in either the ECC or the electron-loss-to-continuum (ELC) channels. An unsuccessful search[4] for ECC interference structure in 0.5-MeV/amu He^{++}-He collisions was, however, made by Duncan *et al.*[4] Within error limits, our more recent experiments on ECC for 1.6–3.9-MeV/amu C, O, and Si bare ions traversing He, Ne, and Ar do not exhibit interference structure.[5] Menendez *et al.*[6] 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 $\vec{v}_e = \vec{v}_{\text{ion}}$ and proposed to explain the observed structure as resulting from two additive processes, namely single and double electron loss in the forward direction.

We report here the observation of pronounced and unexplained oscillatory structure in the wings of the ELC forward peak for 1.6–3.9-MeV/amu O^{4+} and $Si^{10,11,12+}$ 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^{q+} and Si^{q+} projectiles other than those already listed but no detectable oscillatory structure is seen for the bare ions.

The apparatus and methods employed in this work on ELC are essentially unchanged from our earlier ECC studies. Since dimensions, techniques, and other appropriate details are discussed in Ref. 5, most of this detail will not be repeated here. All of the Si^{q+} and the higher-energy O^{q+} on Ne and Ar data were obtained using the Brookhaven National Laboratory tandem accelerator. The lower-energy O^{q+} data were primarily obtained using the Oak Ridge National Laboratory (ORNL) tandem accelerator.

Figure 1 shows energy spectra obtained for electrons emitted in the forward direction using an argon gas target and several O^{q+} and Si^{q+} projectile ions. All spectra displayed are for projectiles having the same velocity (2.5 MeV/amu). 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[5] 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 for O^{5+} about 2.2 times greater than a similarly defined yield for O^{8+}. The fraction of ECC can be estimated assuming an effective ion charge of $Z_{\mathrm{eff}}=q$ by scaling the known O^{8+} yield by $Z_{\mathrm{eff}}^{2.2}$. We have previously confirmed in other experiments[5] this single-power $Z^{2.2}$ scaling for bare ions C^{6+}, O^{8+}, and Si^{14+} in the energy range 1.6–3.9 MeV/amu. Subtraction of a $Z_{\mathrm{eff}}^{2.2}$-scaled ECC contribution from total yields obtained in studies of yield versus projectile charge state results in ELC yields which for O^{q+} on Ar have very nearly the same charge-state dependence as data from Macdonald and Martin,[8] for electron loss for the same projectiles, target, and projectile energy. Extension to lower-charge states of the ECC contribution elimination according to this procedure shows that for 1.6–2.5-MeV/amu O^{q+} projectiles where L-shell electrons are present the ELC yield dominates the ECC contribution. For O^{5+} at 2.5 MeV/amu 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^{5+}, O^{4+}, and O^{3+} are indicative of ELC processes. We observe a similar qualitative behavior in peak-shape variation for the Si^{q+} charge states where, for $q=11$, ELC and ECC contributions are comparable.

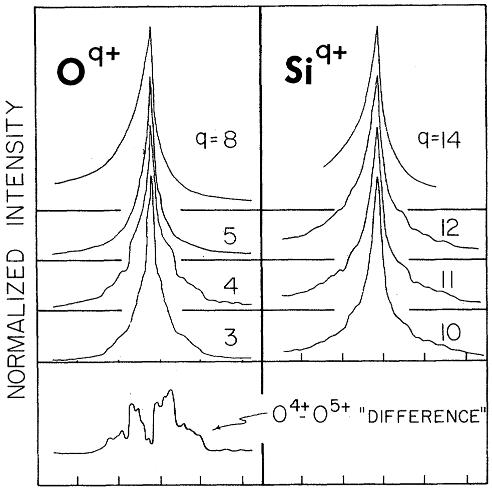

FIG. 1. Normalized spectra for electron capture and loss to continuum states in the forward direction for 2.5-MeV/amu O^{q+} and Si^{q+} on Ar. Zero-count base lines are shown for each spectrum. Statistical errors are about 2% at the peaks. The "difference" spectrum in the lower left-hand portion of the figure results from direct subtraction of the O^{5+} from the O^{4+} normalized data.

The displayed spectrum for O^{4+} shows pronounced oscillatory structure in both wings of the cusp. To make this structure visually obvious, the normalized O^{5+} spectrum, which represents a symmetric and nearly structureless cusp, was directly subtracted from the O^{4+} cusp. This O^{4+}-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. We note that near the cusp a finite electron-energy interval in the laboratory system corresponds to a much smaller interval in the projectile rest frame. For example, 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 a kind of nonlinear electron-energy interval amplification resulting from purely kinematic considerations. Beyond the resolution advantages, the detection advantages of observing ~keV electrons instead of few-eV electrons are very clear.

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/amu) and in all cases the strongest oscillatory structure has been evident for O^{4+} projectiles.

Measurements for the same projectiles (O^{q+} and Si^{q+}) 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.

The laboratory-frame energy positions of the structural features in the "difference" spectrum vary as a function of beam velocity but when viewed in the projectile rest frame are found to be almost independent of beam velocity. The minor variations observed might be due to kinematic effects. 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.

Data obtained under precisely the same experimental conditions with Si^{q+} projectiles are displayed in the right-hand column of the figure. Oscillatory structure in the wings similar to that for O^{4+} 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^{q+} with $q<10$ (as for O^{3+}) no clear oscillations have been observed. As in the O^{q+} 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^{4+} spectra are differently spaced and scale, in the projectile rest frame, approximately with Z_1.

The wide range of charge states used for Si^{q+} on Ar ($q=5-14$) gives rise to a monotonically decreasing ELC cross section with q, producing a factor of ~10 drop in going from $q=5$ to $q=11$. Here the ELC cross section is taken to be proportional to the yield per projectile ion obtained by integrating over the cusp between velocity limits $(1\pm\alpha)v_i$, where α is arbitrarily but consistently chosen to be ~0.04 and v_i is the projectile velocity. 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[9] 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/amu) 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[5] ECC cross sections.

To summarize, reproducible oscillatory structure in the wings of the forward electron peaks for Si^{10+}, Si^{11+}, Si^{12+}, and O^{4+} on Ar and Ne at several projectile energies has been observed. At this time the origin of this structure is very unclear and therefore several experiments were carried out to determine the dependencies on the available variables. The parameters varied in these experiments include the projectile (Z_1), the projectile charge state (q), the projectile velocity (v_i), and the target (Z_2). Studies involving variation of each of these parameters lead to the following 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^{q+} (less so for Si^{q+}) and weakly dependent on v_i. (3) The "positions" are dependent on Z_1 and, in the projectile frame, appear to scale approximately with Z_1. (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 discussed. The observed oscillatory structure has periodicity, especially obvious in the far wings of the $Si^{10,11,12+}$ 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.

It is noted that in the O^{q+}-Ar data of Ref. 8, the ratio of total cross sections for two-electron to one-electron loss $\sigma_{q,q+2}/\sigma_{q,q+1}$ increases with decreasing q. For O^{4+}, where the strongest structure has been found, this ratio is (10–30)% in the energy range studied. One can therefore speculate about multiple-electron transitions in ELC leading to the observed structure. For O^{3+} at 2 MeV/amu Macdonald and Martin[8] find that the probability for losing three electrons is comparable to that for two electrons. Thus structure due to one process might easily wash out that due to the other and yield the observed nonoscillatory structure for O^{3+}. Unfortunately, there are no total loss cross sections available for Si^{q+} with which one can make similar comparisons. 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^{q+} (with $q \leq 10$). One can 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, although for O^{4+} ELC is much more probable than ECC (~20 times more probable).

For multiple loss processes, it has not been possible to determine from our data whether interference or electron repulsion effects without interference might be responsible for the observed structure. However, the approximate independence of the projectile-frame energy of the structural features on the specific initial electron configuration of the projectile (i.e., independence of q) and the observed periodicity tend to indicate an interference phenomenon.

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