Production of highly charged low-velocity recoil ions by heavy-ion bombardment of rare-gas targets

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The author has measured charge-state (q) spectra of recoil ions generated in single collisions of 25–45-MeV chlorine ions with targets of helium, neon, and argon. A high-efficiency time-of-flight spectrometer was used to identify the charge-to-mass ratio of the slowly moving recoils. Recoil q up to $+8$ (neon) and $+11$ (argon) were observed. Cross sections for recoil production were measured as a function of projectile energy and incident charge state. The energy dependence of the cross sections is quite weak, while the recoil-q dependences show clear shell effects in argon. For the lower-q recoils, the cross sections are reasonably well described by the model of Olson, which treats the target electrons as moving independently. For higher q, a model based on energy deposition by the projectile with the target electrons, followed by statistically weighted electron emission, gives a better description of the data.

I. INTRODUCTION

When a sufficiently fast-moving highly charged ion passes a target atom at a distance of a few atomic units or less, it may, with large probability, eject a number of the target electrons without simultaneously imparting much energy to the target center of mass (c.m.). This result is due to the large ratio of target nuclear mass to that of the electron. A number of experiments in recent years have made it evident that highly charged slow-moving recoils are produced in collisions sufficiently violent to produce inner-shell excitations. For example the shift to higher energy of target K x rays produced by heavy-ion bombardment was reported by Richard *et al.*[1] in 1969. This effect was quickly shown to be due to the high level of L-shell and higher-shell ionization which accompanies K-vacancy production, and the subject has subsequently been heavily studied.[2] K-x-ray spectra from 40-MeV Cl on Ne have shown evidence for removal from the Ne, in a single collision, of all but a single electron.[3] The K-Auger spectrum from 200-MeV Xe on Ne was found to be dominated by decay from Li-like neon, in sharp contrast to the complex K-Auger spectrum from lower ionization states of neon generated by less destructive beams.[4] Spectral analyses have been made[2,5] in order to extract probabilities for production of the various levels of L ionization accompanying K ionization, and single L-electron removal probabilities P_L have been extracted. Such results give P_L characteristic of small impact parameter (b) collisions only, and give no direct information on the total cross sections for L-shell ionization. More recently Mann *et al.*[6] studied the broadening of K-Auger lines from molecular targets caused by the Coulomb "explosion" of the recoiling target fragments from one another following simultaneous removal of one K-shell and several higher-shell electrons.

In this paper we present results of measurements of production cross sections for the generation of highly charged argon and neon recoils by 25–45 MeV Cl $+q$ beams. Charge states up to Ar^{+11} and Ne^{+8} were observed, with c.m. recoil energies typically less than 30 eV. Such recoils are of considerable interest largely because the energy associated with the electronic excitation is larger than that of their center-of-mass motion. This is the opposite of the case for foil, or collisionally-excited *projectiles*, whose center-of-mass energy is typically greater than their electronic excitation energy by a factor near the nucleus-to-electron mass ratio. The thermodynamic state of the recoil resembles much more nearly that of an ion in a hot plasma than does the state of the projectile. The recoil thus affords an opportunity for the study of the relatively stationary "hot" ion, its spectroscopy, lifetimes, etc. Further, such recoils are available as slow-moving projectiles which may be directed onto a secondary target in order to study collisions involving very highly charged projectiles in the very low-energy regime.

Numerous cross sections for multiple electron loss by fast *projectile* ions in collision with neutral targets have been reported previously. This subject is included in the review article by Betz,[7] who pointed out that almost no theoretical work on multiple ionization cross sections was available at the time. Those measurements are similar in some respects to those reported in this paper, with projectile and target roles interchanged. They differ from our experiments in that the system whose charge change is detected has collided with a neutral target, rather than the highly charged collision partner which we can use as a projectile. They of course differ markedly in a practical way, in that the observed ionized reaction products are the fast-moving projectiles rather than the slowly moving target recoils which we observe. Several measurements of single-target-ionization cross sections have been reported for proton bombardment.[8,9] There does not appear to be corresponding data for resolved higher target ionization states.

There is a great body of literature (for example, see Refs. 10–17) on the charge-state distributions of both projectile and target recoils from experiments of the 1950s and 1960s especially for Ar^+ and Ne^+ on similar targets at bombarding energies below 400 KeV. These experiments were all differential in nature and showed that violent collisions which result in wide angle scattering of the projectile produce prodigious ionization of both projectile and target. A particularly interesting conclusion was drawn by Everhart and Kessel[16] that the charge-state distributions of the collision partners were uncorrelated, provided inner-shell vacancy producing collisions were avoided. As will be shown in a subsequent paper, this result is not at all true for the collisions discussed here. Our experiments address a quite different physical regime in that the projectiles used here are higher in energy by nearly two orders of magnitude, thus making the collision time short compared to outer-shell electronic frequencies. Further, our projectiles are very highly stripped and hence they have a smaller electronic radius than the target outer shells, thus allowing their treatment as approximate point projectiles.

II. EXPERIMENT

A. Overview

The apparatus used in producing and identifying the recoil ions is shown schematically in Fig. 1. A pulsed beam of chlorine ions in a preselected charge state was provided by the University of Aarhus tandem Van de Graaff facility. This beam impinged upon a gas target, the interaction region being located in an approximately uniform electric field directed at right angles to the beam. Recoil ions generated in this region are thus swept toward a channeltron detector located some distance away. Since the recoil energy from the collision is small compared to q multiplied by the accelerating potential, the average post-acceleration velocity of the recoil is independent of the recoil angle, and is proportional to $\sqrt{q/m}$, where q and m are recoil charge and mass, respectively. Thus the flight-time spectrum gives a direct measure of the recoil charge state spectrum.

B. Time-of-flight spectrometer

The beam pulses were independently determined to be approximately Gaussian in shape with full width at half maximum (FWHM) less than 3 nsec. A pulse-repetition time of 4 μsec was used for most runs to avoid overlap of spectra from successive pulses. The average beam current on target was typically kept below 10^{-10} A in order to prevent significant dead time losses in the analog-to-digital converter.

The interaction region was defined in lateral extent by a 0.3×0.6 mm entrance aperture, the smaller dimension being in the direction of recoil extraction. The length of the interaction region was originally the same as that of the gas cell, 1 cm. However, it was found necessary to use a slit to limit (to about 1 mm) the length viewed by the channeltron, in order to avoid different flight times to the detector from different positions along the interaction length.

The acceleration grid was a Ni mesh with a transmission near 60% located 3 mm above the beam axis. Negative extraction voltages (V_g in Fig. 1) between 200 and 1500 V were used on this grid with final cross section results all taken at 772 V. The flat bottom of the gas cell, located 2 mm below the beam, provided the ground electrode. The flight path to the channeltron was approximately 4 cm. The channeltron anode (V_{coll} in Fig. 1) and cathode voltages could be varied independently, with typical values being +500 and −2200 V, respectively.

Standard leading edge timing electronics were used to generate a fast signal from the arrival of a recoil in the channeltron. This signal was used to start a time-to-amplitude converter (TAC), which was stopped on the master clock of the pulsing system. The overall time resolution of the system as measured by the width of the photon peak for the argon target was 8 nsec (FWHM). Time resolution on the ions was limited by the variation of path length traveled to different points on the channeltron cone and was never better than 20 nsec.

Typical time spectra for neon and argon targets are shown in Figs. 2 and 3, respectively. It was found that the residual-gas background was dominated by water vapor, giving rise to peaks from H_2O^+, OH^+, O^{+q}, and H^+, the last being the strongest single contaminant line. Rather than attempt to purge the system of this background, it was found easier to simply subtract its contribution from each spectrum before analysis. Indeed, the partial pressure of H_2O was found to be sufficiently constant that the proton recoil peak could be used as an independent check on the relative beam

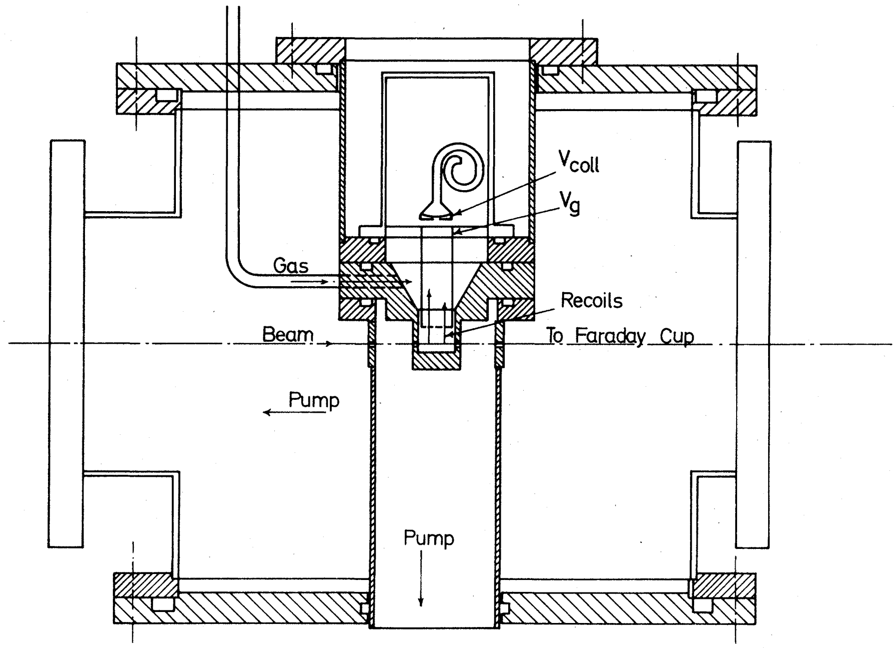

FIG. 1. Schematic of apparatus.

charge delivered during a run.

One may obtain an approximate upper limit on the initial recoil energy from the width of the peaks in charge state spectra such as Figs. 2 and 3, provided one knows the geometry of the time-of-flight spectrometer. The result depends on the acceleration voltages and collision parameters, of course. As an example, for 34-MeV Cl^{+12} on neon, we were able to deduce approximate upper limits of 5 and 30 eV on the initial energies of the +2 and +7 recoils, respectively. In fact, we believe the true energies may be much less than this. For example, a heavy 1 MeV/amu point charge with charge +12 passing 0.2 Å from a ^{20}Ne nucleus would transfer only about 4.5 eV to that nucleus. From the size of our measured cross sections, we estimate this impact parameter to be at least as small as that characteristic of the production of the highest recoil neon ions observed.

We mention that bombardment of diatomic molecular targets such as O_2 and N_2 yield qualitatively very different spectra with much broader and often overlapping peaks. This occurs because of the large initial energies imparted to the recoils by their mutual repulsion from the Coulomb "explosion". Some related energy spectroscopy on the fragments produced by fast ion bombardment of molecular targets has been reported previously.[18]

C. Pressure dependence

In Fig. 4 we show the yields, per unit beam charge, of neon recoil ions in selected charge states as a function of the gas cell pressure. This pressure was measured by a pirani gauge which was in turn calibrated against a capacitance manometer. The data are normalized to the yield at a target pressure of 5×10^{-4} torr so that they fall on a common curve, which appears linear below 10^{-3} torr. Cross-section measurements were all made at a pressure of 3.8×10^{-4} torr. Although this may seem at first rather high for such slow, highly charged ions, we point out that charge exchange must occur within a flight path of 3 mm in order to invalidate the charge identification. For example, a charge-changing cross section of 10^{-15} cm^2 would induce only a 0.4% charge impurity over a distance of 3 mm at this pressure. Charge loss during the remaining 4-cm flight path causes a slight change in transit time due to the final acceleration into the channeltron cone. Evidence for this effect is seen in the structure on the lower-q peaks in Fig. 3.

D. Absolute cross-section determination

Yields of recoil ions per integrated beam charge were measured at a fixed-target gas pressure. These were placed on an absolute cross-section scale by measuring the corresponding yields of singly charged recoils from 2.14-MeV proton bombardment and by normalizing to the cross sections of Pivovar and Levchenko.[9] (These standard cross sections for single target ionization were taken as 0.12, 0.30, and 0.80×10^{-16} cm^2 for 2.14-MeV protons on targets of helium, neon, and argon, respectively.) We note that the helium cross section

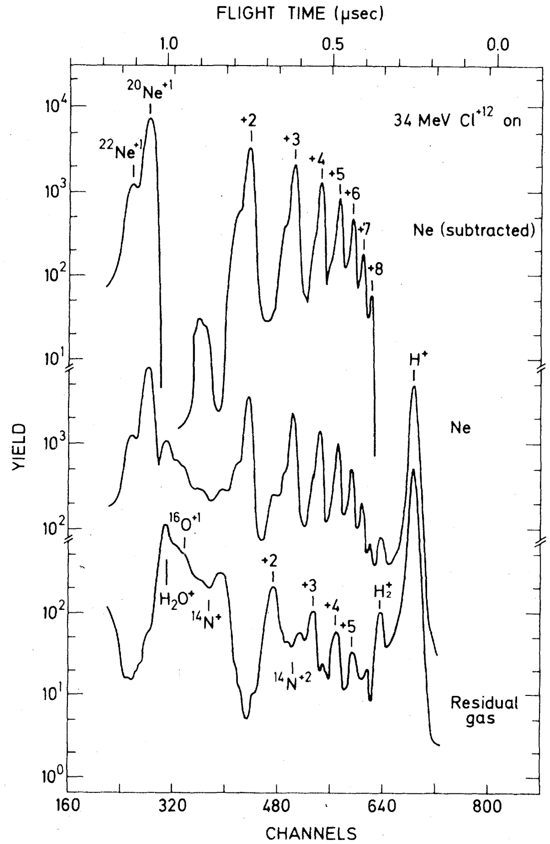

FIG. 2. Time-of-flight recoil spectrum for 34-MeV Cl^{+12} on residual gas and on neon plus residual gas. The uppermost curve is the difference between these spectra.

is in rather good agreement with that expected from a Bethe-Born calculation at this energy.[19]

This procedure is valid if the efficiency of the time-of-flight spectrometer is not dependent on recoil q. To investigate this point, we made two tests. The energy of the ions into the channeltron was varied by floating the entire detector voltage, while holding constant the anode-cathode potential difference. The results indicated no dependence of channeltron efficiency on ion energy, within 10%, above an ion energy of 1 keV. The channeltron voltages were then fixed- and charge-state spectra were taken at various grid voltages. There was a weak dependence of absolute yields on V_g, less than 20% for $200 \leq V_g \leq 1500$. No changes in relative yields of various charge states were found.

As an independent check on our absolute cross sections, we may compare our results with those of Berkner *et al.*,[20] who have measured the quantity $\sum_i i\sigma_i$ for carbon and Fe projectiles on helium, neon, and argon. Here σ_i is the cross section for producing a recoil in the ith ionization state. A comparison of their results with the corresponding sum formed from our data is made in Table I. Our cross sections appear to be systematically slightly above theirs. This is especially apparent for the comparison of our data for Cl^{+6} on Ne and Ar with theirs for C^{+6} on those targets. It is not unreasonable to expect that, at impact parameters important for these targets, the Cl nucleus is not fully screened by its 11 electrons, and thus might produce heavier target ionization than does the bare carbon nucleus. This point is discussed further later. The experimental uncertainty on the standard cross sections to which we are normalizing appears to be about 10%. Our own results reproduced absolutely from one day to the next to

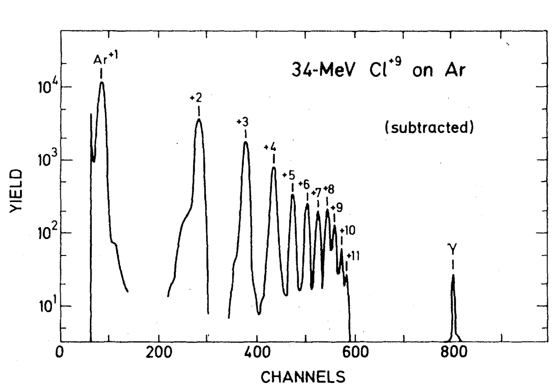

FIG. 3. Time-of-flight recoil spectrum for 34-MeV Cl^{+9} on Ar.

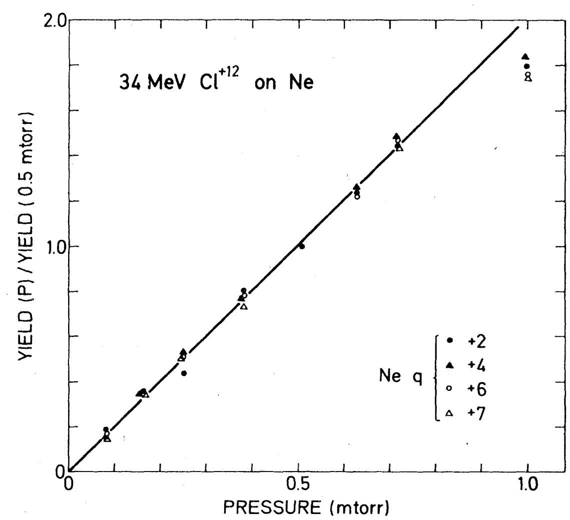

FIG. 4. Recoil yields for selected recoil charges q for 34-MeV Cl^{+12} on Ne as a function of cell pressure. The yield for each q has been normalized to unity at 0.5 mtorr.

TABLE I. Comparison of $\sum_i i\sigma_i$ from different sources.

Projectile	E (MeV/amu)	Target	$\sum_i i\sigma_i$ ($\times 10^{-16}$ cm^2)	Reference
C^{+6}	1.00	He	6.2 ± 1.5	a
Cl^{+6}	0.97	He	8.0 ± 2.0	b
C^{+6}	1.00	Ne	16.6 ± 4.0	a
Cl^{+6}	0.97	Ne	28.2 ± 7.0	b
C^{+6}	1.00	Ar	37.0 ± 9.0	a
Cl^{+6}	0.97	Ar	67.0 ± 17.0	b
Fe^{+12}	1.00	Ar	133.0 ± 53.0	a
Cl^{+12}	0.97	Ar	152.8 ± 38.0	b

[a] Berkner *et al.*, Reference 20.
[b] Present results.

within about 10%. Taking into account these factors in addition to uncertainties in charge integration and background subtraction, we place an error bar of 25% on our absolute cross-section scale. The relative uncertainties in any given figure are much smaller than this, in most cases being approximately the symbol size or smaller. One must bear in mind the uncertainty in the overall absolute σ scale when making comparisons between theory and experiment.

III. RESULTS AND DISCUSSION

Figures 5–9 display plots of our measured cross sections versus bombarding energy E, projectile charge state, and recoil charge state i. Several qualitative features may be summarized. (i) The σ_i are very weakly E dependent in this energy range, decreasing slightly with E. This is to be expected, since the projectile velocity scaled to that of the outer-shell target electrons is substantially greater than unity. (ii) σ_i for low i increases with projectile charge Q much less rapidly than Q^2. This increase is more marked for larger i. (iii) For the case of argon, the plot of σ_i vs i displays shell structure near $i=7$. Indeed, cross sections for production of final charge states 7 and 8 are nearly equal.

We have compared our experimental cross sections with the results of two types of model calculation.

A. Independent-electron ejection model

If the collision time is sufficiently short compared to the characteristic orbital times of the outer-shell electron, an approach which has often been followed in the literature is to assume that the ejection of a particular electron proceeds with a probability independent of the fate of the remaining electrons. As summarized by McGuire and Weaver,[21] if the b-dependent probability for ejecting a single electron from a given shell of N electrons is denoted as $P(b)$, then the probability $P_n(b)$ for ejecting n electrons in a collision is found, using binomial statistics, to be

$$P_n(b) = \binom{N}{n} P(b)^n [1 - P(b)]^{N-n}, \quad (1)$$

and the cross section σ_n for ejecting n electrons is

$$\sigma_n = \int 2\pi P_n(b) b \, db \,. \quad (2)$$

Here $\binom{N}{n}$ is the binomal coefficient for selecting n outgoing electrons from a total of N electrons. This procedure has recently been used by Olson[22] to calculate values for σ_n for our cases. He obtains $P(b)$ from a classical-trajectory Monte Carlo (CTMC) calculation in which the projectile is treated as a point charge. The target electron is treated as hydrogenic, moving about a nucleus whose effective nuclear charge Z_{eff} is chosen to provide a reasonable radial probability distribution and the correct single-electron-binding energy. He has modified Eq. (1) to take into account the different contributing subshells.

The results of his model calculation are compared with the present data in Figs. 5–7 and 9. The major failing of the model seems to be its overestimate of σ_i for large i. We believe this to be due to the fact that the effective single-electron removal probability $P(b)$ is quite sensitive to the binding energy of the electron to be removed, and this energy, for the present case of outer-shell electrons, increases rapidly with the ionization state of the final recoil ion. For example, the ionization potential for neutral neon is only 21.5 eV, while that for the Ne^{+5} is 507 eV. The more electrons one removes, the more difficult it becomes to remove the next one. Thus, $P(b)$ calcu-

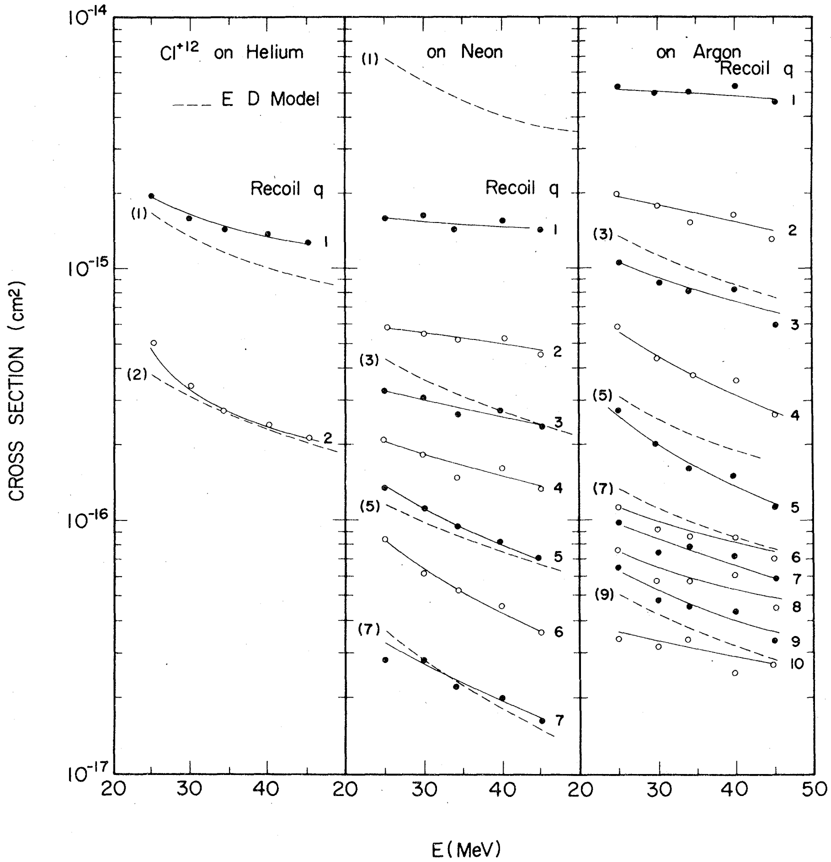

FIG. 5. Cross sections for the production of recoils in charge state q by a Cl^{+12} beam as a function of bombarding energy. The solid lines are to guide the eye only. The ED model results for selected values of q are shown as dashed lines.

lated on the basis of removing a single electron predicts too high a value for $P_i(b)$ for larger values of i. We note that this effect will lead the model to overestimate $\sum i\sigma_i$ for the neon and argon targets especially.

B. Energy deposition model

A second approach follows the statistical treatment of multiple electron removal developed in the 1950s and 1960s by Russek and collaborators.[23,24] In this model the ionization process is viewed to proceed in two steps. (i) The projectile and target collide, depositing a part of the energy originally in the translational motion of the systems as electronic excitation energy of the collision partners. (ii) After the partners depart from one another, excess electronic energy residing in each partner is distributed among its electrons and the system subsequently autoionizes to reach its final ionization state.

Whereas we may take the treatment of the second step from the work of Russek and Meli (RM),[24] treatment of the first step must be tailored to the conditions attending our collisions. The energy deposition process presumably proceeds quite differently in our high-velocity case from the way it does in the low-energy experiments. In the low-velocity experiments molecular-orbital promotions played an essential role in the energy deposition processes, and indeed Everhart and Kessel[16] found it necessary to modify the simplest assumptions of the statistical model to allow for the Auger ejection of at least one nonstatistically fast electron prior to the evaporation process. In our cases, the projectile moves rapidly compared to the motion of the outer target electrons. For example, a 1 MeV/amu projectile is moving at a velocity five times that of a 21.5-eV electron, the latter energy being the first ionization potential of neon. Since the projectile is usually spatially small compared to the target shells of interest, we view the energy deposition to be roughly that due to the fast passage of a point charge through a cloud of free-target electrons.

We have applied the energy deposition (ED) model to our case in the following way.

(i) The energy transmitted to the electronic coordinates of the target was calculated in the simplest classical impulse approximation. The Bohr parameter[25] $\chi = (2Ze^2/hv)$ is typically near three for our conditions, which might seem to marginally qualify the use of a classical calculation. (Z and

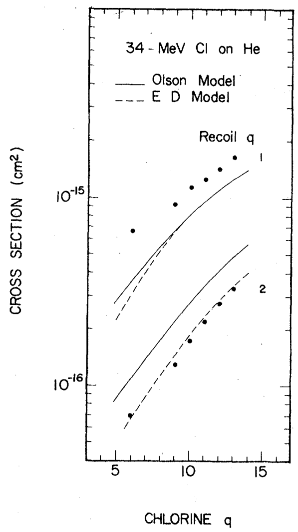

FIG. 6. Cross sections for the production of recoils in charge state q as a function of projectile charge for 34-MeV Cl on He. Predictions of the Olson and ED models are shown as solid and dashed lines, respectively.

v are projectile charge and velocity, respectively.) However, we are not interested in angular distributions, to which this parameter primarily applies. The criterion that the de Broglie wave length of the projectile, 0.8 fm for a 34-MeV Cl ion, be small compared to the dimensions of the scattering center is easily met. The projectile was treated as a point charge, a treatment probably good for high-projectile charge or low-recoil ionization state, but which may fail as one departs this region.

The energy transmitted to a free electron by the passage of the projectile on a straight-line trajectory at impact parameter p is given by[26]

$$T(p) = (2Z^2e^4/mv^2)/(p^2+a^2)\,, \tag{3}$$

where $a = Z(M+m)e^2/Mmv^2$, and M and m are projectile and electron masses, respectively.

The energy E transmitted to the entire atom by the passage of the projectile at an impact parameter b with respect to the target nucleus is found by integrating $T(p)$ over the spatial probability distribution of each electron and summing over the i electrons in the target

$$E_T(b) = \sum_i \int |\psi_i(\vec{r})|^2 T(p)\, d^3\vec{r}\,, \tag{4}$$

where p is a function of b and $\vec{r}$. The integrals for $E_k(b)$ were performed numerically using Slater screened[27] hydrogenic wave functions for the ψ_i. The final results are not very sensitive to the exact form of the wave functions, because much of the energy transfer occurs for b outside the mean radius of the target electrons.

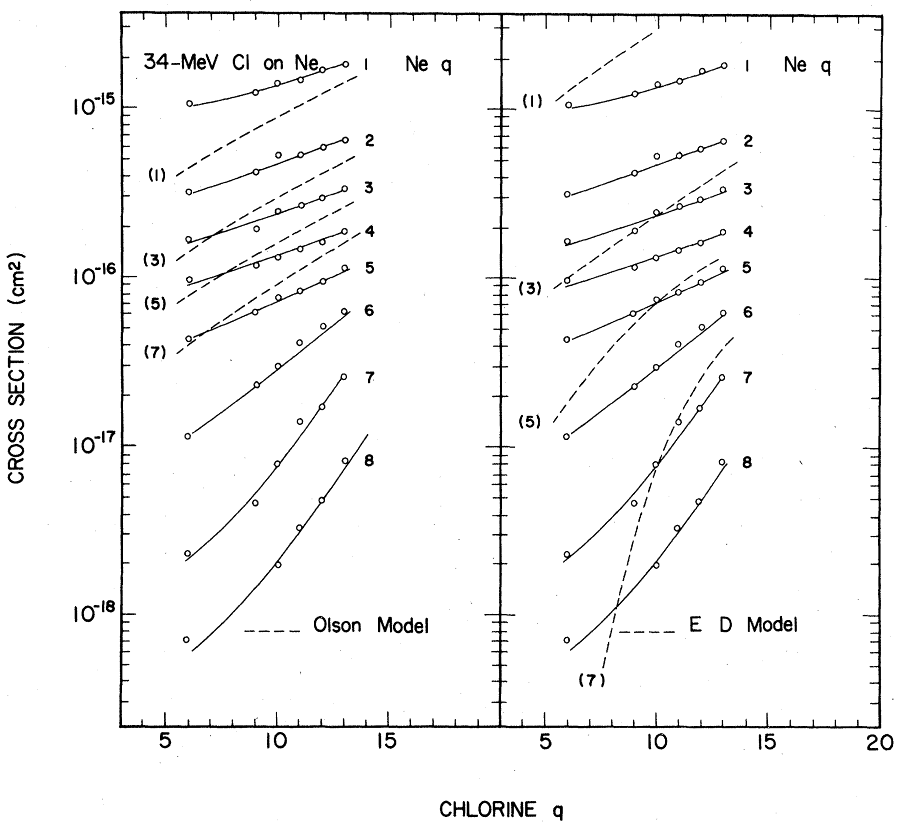

FIG. 7. Cross sections for the production of recoils in charge state q as a function of projectile charge for 34-MeV Cl on Ne. The solid lines are to guide the eye through the data. The Olson and ED model results for selected values of q are shown as dashed lines in left- and right-hand parts of the figure, respectively.

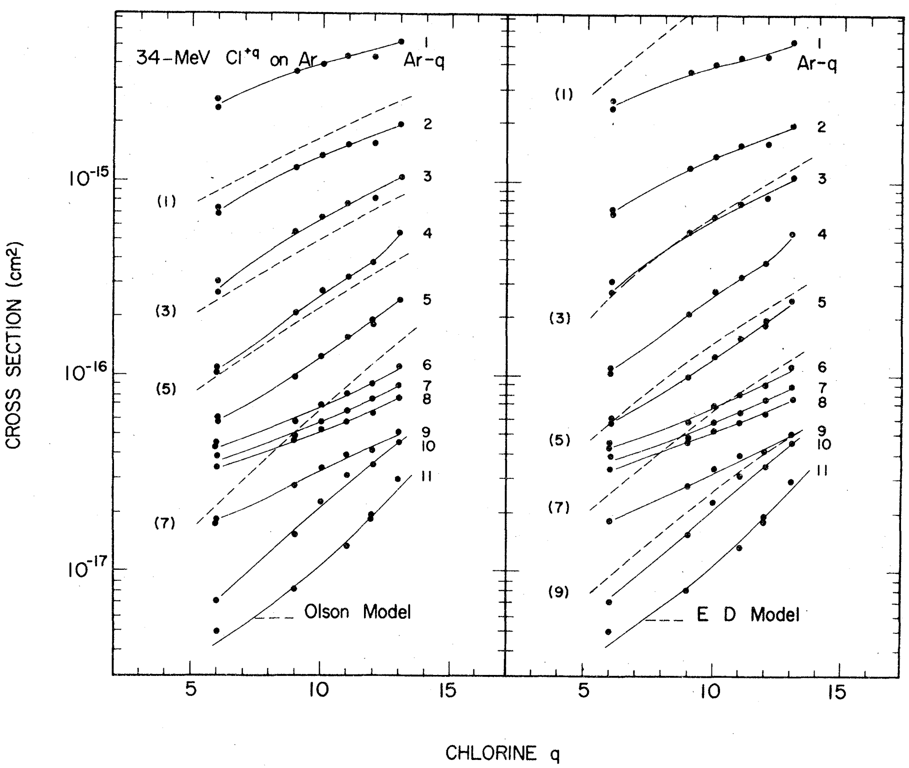

FIG. 8. Similar to Fig. 7, but for an argon target.

(ii) The probability of achieving a final charge state i, given an energy deposition $E_T(b)$, was taken from RM [Eq. (19) in Ref. 24]. Their result (with their average matrix element g set equal to unity) gives a probability for each final state which is proportional to the volume of phase space available in that ionization state. The expression is

$$P_n(E_k) = \binom{N}{n} S_n(E_k/\epsilon_1) , \quad (5)$$

where E_k is the kinetic energy available to the electrons if the residual ion is left in the nth ionization state, and ϵ_i is the ith ionization energy. E_k is related to the energy deposited with the atom by $E_K = E_T - \sum_{i=1}^{n} \epsilon_i - E_R$, where E_R is the residual excitation of the remaining ion. The integrated volume of phase space available in the nth ionization state, S_n, is as given by RM in Eq. (15). Those authors found that, for collision conditions in which the outer shells were highly excited, expression (5) gave a very good description of the experimentally found charge-state distributions as a function of inelastic energy loss for $Ar + Ar^+$ collisions.[15,16]

Using expressions (4) and (5), we obtained P_n as a function of b, and calculated σ_n from (2). In Fig. 10 we show a sample set of $P_n(b)$ curves, as well as $E_T(b)$, for the case of a 1 MeV/amu 9^+ projectile on neon. The K shells of neon and argon targets, whose electrons are not moving slowly compared to the projectile velocity, were considered inert in the calculation. All other electrons were allowed to participate. We remark that within this model, at a given b, there are generally not more than two or three major charge states populated. A strong correlation between final recoil q and b is thus predicted. The b dependence of a given charge state tends to be somewhat more localized in this model than was found in Olson's calculation.[22]

The results of the ED model with $E_R = 0$ are shown in Figs. 5–9. Above the first ionization state, the cross sections are rather well reproduced. In order to check the sensitivity of the results to the degree of excitation of the residual ion, we also calculated σ_n arbitrarily setting E_R equal to the first ionization potential (15.5 and 20.1 eV for argon and neon, respectively). The resulting values for σ_1 were two to three times lower, showing the sensitivity of especially the ionization of the outermost electrons to energy loss by photons. The effect was less than 10% above the third ionization state. It is not surprising that some of the excitation energy should be radiated away, perhaps especially near the closed shell systems where radiating metastable states may be formed. The model accounts for the shell structure seen in the argon case for n between 8 and 9. A considerable range of energy loss goes into the gap between the last

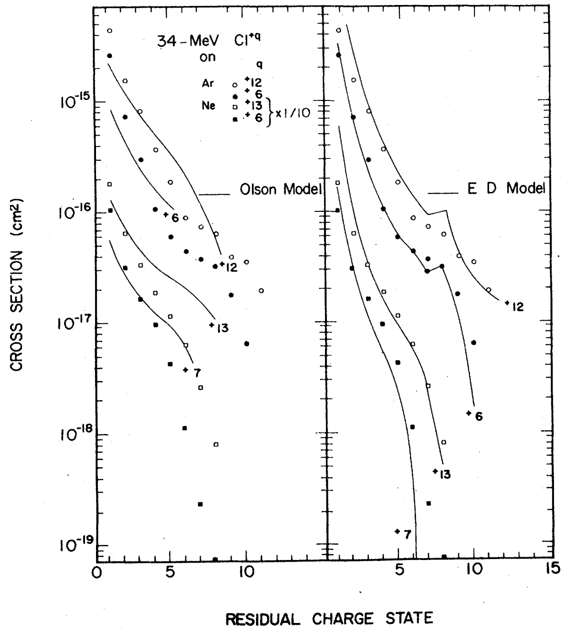

FIG. 9. Cross sections for the production of recoils in charge state q for 34-MeV Cl in selected charge states on targets of argon and neon. The neon data have been divided by 10 before plotting. The Olson and ED model results are shown as solid lines in the left- and right-hand parts of the figure, respectively. The model results are labeled by the effective projectile charge used in the calculation.

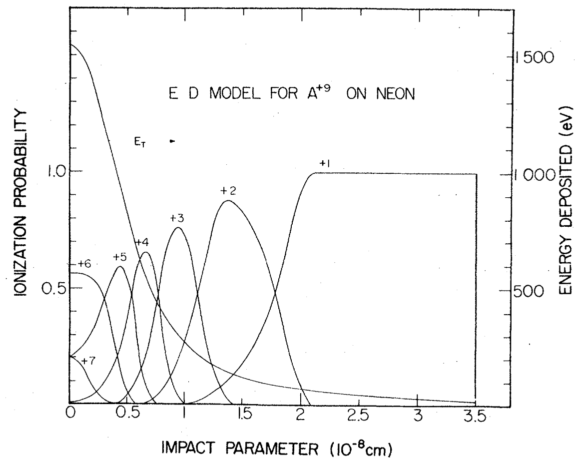

FIG. 10. Plots vs impact parameter are given for (a) the calculated energy E_T deposited with the electrons of a neon target by a 1-MeV/amu +9 projectile, and (b) the corresponding ionization probabilities [P_n, Eq. (5) in text] from the ED model (see text).

M electron and the first L electron.

The single-ionization cross section is consistently overestimated by the model. This may be due to the failure of the impulse approximation, since large contributions to σ_1 come from $b\sim 3$ Å. The adiabatic radii $hv/\Delta E$ for the first excitation of neutral neon and argon are 4.2 and 5.8 Å, respectively, not very much larger than b. For large b, the electron cloud will react more adiabatically to the projectile's perturbation and the impulse approximation will overestimate the energy transfer. Further, much of the single-ionization cross section comes from a b region where the energy transfer per L (or M) electron is considerably below the energy required to even excite the closed-shell target. The classical calculation should strongly overestimate the energy transfer in this region. This effect should be much weaker for helium, where there are fewer electrons to share the energy and where much smaller b values are important. It should also be weaker for the other targets above the first ionization state, where the energy required to reach the first excited states is a smaller fraction of the ionization potential.

The model underestimates significantly the production of higher charge states for Cl^{+6} on Ne. This may be due to the assumption that the projectile nuclear charge is fully screened by its accompanying electrons. For example, the major contribution to σ_5 in this case is predicted to come near an impact parameter of 0.5 Å. This is already less than the most probable radius of the lone M electron of 0.7 Å (assuming screening by the L electrons). For this reason we compare these data with the model results calculated for a +7 incident ion. For the higher projectile charges this effect would be expected to be less pronounced.

IV. CONCLUSION

We have presented experimental cross sections for the production of low-energy highly charged recoil ions by bombardment with fast, highly stripped ions. The classical trajectory Monte Carlo calculation of Olson[22] gives a fair description of the single-ionization cross sections, but predicts too much multiple ionization. Many features of the higher ionization-state data are accounted for the the energy deposition model in which electronic excitation and electron removal are viewed to proceed as separate steps. It might appear at first glance that one should conclude that the contribution of electron capture by the projectile to σ_n is likely to be small. In fact, it is not clear that this is so, or even required by the model. The ED model in principle takes into account all phase space available to the outgoing electrons. Much of this phase space, especially the higher-momentum part attained electrons in the more violent collisions, may be that which is occupied by electrons bound to the projectile. Thus it is not clear that the model excludes capture contributions particularly for small *b* collisions. The present data do not address the question of possible correlations between charge changes on projectile and target. This problem must be attacked by using coincident detection of recoil and projectile charge state, and is the subject of a subsequent paper.

The cross sections are as large as 4×10^{-15} cm^2 for single ionization of argon by Cl^{+12} and remain at least of order 10^{-16} cm^2 through charge 8 for this target. These large cross sections, together with the high extraction efficiency which can be obtained, lead us to believe that it is entirely feasible to use these highly charged systems as projectiles in further experiments. This would apparently represent a novel technical approach to the study of the interaction of slow but highly charged ions with neutral targets.

V. ACKNOWLEDGMENTS

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