Charge-state correlated cross sections for the production of low-velocity highly charged Ne ions by heavy-ion bombardment

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We report measured cross sections for the collisional production of highly charged low-velocity Ne recoil ions resulting from the bombardment of a thin Ne gas target by highly charged 1-MeV/amu C, N, O, and F projectiles. The measurements were made using time-of-flight techniques which allowed the simultaneous identification of the final charge state of both the low-velocity recoil ion and the high-velocity projectile for each collision event. For a given incident-projectile charge state, the recoil charge-state distribution is very dependent upon the final charge state of the projectile. Single- and double-electron capture events by incident bare nuclei and projectile K-shell ionization during the collision cause large shifts in the recoil charge-state distributions toward higher charge states. A previously proposed energy-deposition model is modified to include the effects of projectile charge-changing collisions during the collision for bare and hydrogenlike projectiles and is used to discuss the present experimental results.

I. INTRODUCTION

The recoil ions produced by the collision of highly charged projectiles with neutral target atoms, for sufficiently fast projectiles, possess very low kinetic energy while simultaneously having a high degree of excitation and/or ionization. Cocke[1] has recently measured charge-state distributions of low-velocity recoils of He, Ne, and Ar produced in collisions with 28–43-MeV-Cl beams, in charge states 6+ to 13+, incident upon thin rare-gas targets. Charge states of 1+ and 2+ (He), 1+ to 8+ (Ne), and 1+ to 11+ (Ar) were observed. The cross sections for the production of these ions as a function of recoil charge state (q) were determined. These data were interpreted with some success in terms of two models,[1,2] each of which attributes the target ionization to the passage of a fast point projectile through the atom. The first of these models, due to Olson (O model),[2] envisages the ionization of totally independent target electrons, while the second (ED model)[1] uses a statistical treatment of electron emission proposed by Russek and collaborators.[3,4] At the impact parameter (b) at which these recoils must be produced, as deduced from the measured cross sections, the recoil energies are expected to be typically less than 10 eV.[1]

These measurements of the recoil charge distributions did not address the question of what happens to the projectile charge state during the collision. Indeed the physical picture emerging from the relative success of the models in predicting the observed cross sections might seem to suggest that the target electrons are simply blown off of the atom rather than captured by the projectile during the collision. In this paper we have investigated this point experimentally by measuring the final charge state of the projectile (via posttarget magnetic analysis) in coincidence with the target recoils produced in collisions with 1-MeV/amu beams of C, N, O, and F.

The experiments reported here are related to a number of earlier coincidence experiments done at lower bombarding energies in which the charge states of both projectile and recoil were identified. These experiments selected violent collisions by requiring a large projectile-scattering angle. Kessel and Everhart[5] showed that the recoil and projectile-charge-state spectra were largely uncorrelated for these cases so long as inner-shell excitation was avoided. If this lack of correlation were generally true, little information about the details of the collision processes could be obtained from coincidence experiments, which was not available from the singles charge-state spectra of either collision partner. In our collisions the initial situation is quite asymmetric with respect to the charge states of the colliding atoms. The projectiles are highly stripped (usually bare nuclei) whereas the target atoms are neutral. Furthermore, the incident ions have incident velocities much larger than the average velocity of the target outer-shell electrons (L-shell electrons in the case of Ne). As the collision time is much smaller than the characteristic orbit time, one does not expect that the target electrons may distribute themselves in anything approaching a symmetric way about the two charge centers as the collision proceeds. On the other hand, one must expect that a certain amount of electron capture by the bare projectile will occur. In contrast to the results for low-energy experiments,[5] we find a strong correlation between the postcollision charge state of the projectile and the recoil charge-state distributions. While the lower charge state (q = 1+, 2+, 3+, . . .) of the recoils appear to accompany projectiles whose charge is unchanged by the collision, electron capture by the projectiles makes an important contribution to the production of the higher recoil charge states (q = 6+, 7+, 8+).

II. EXPERIMENT

The procedures for recoil extraction and identification via time-of-flight techniques were similar to those used by Cocke,[1] except that instead of a pulsed incident beam the current results were obtained with a dc incident beam. The experimental apparatus for the present work is shown in Fig. 1. Beams of C, N, O, and F at 1 MeV/amu from the Kansas State University EN tandem Van de Graaff accelerator were poststripped to the desired incident charge state (usually the bare nucleus), and directed into a differentially pumped gas cell containing Ne gas at a pressure of $<10^{-3}$ Torr. Charged Ne recoils generated by collisions in the cell were extracted by an electric field directed at right angles to the beam direction and accelerated into a drift tube for detection by a channeltron detector located 13 cm from the interaction region. The extraction field was produced by a 500-V potential difference placed across the gap (5 mm) between two 80% transmission nickel grids. The drift tube contained sets of parallel plate deflectors and an einzel lens which improved the overall transmission of the recoils from the interaction to detection regions.

The time of flight of a recoil of mass m and charge q to the detector is proportional to $\sqrt{m/q}$ for a fixed extraction voltage on the lower grid in Fig. 1. This time was measured by starting a time-to-amplitude converter (TAC) with the signal produced by a recoil ion in the channeltron. The stop signal for the TAC was provided by the detection of the charge-state analyzed projectile

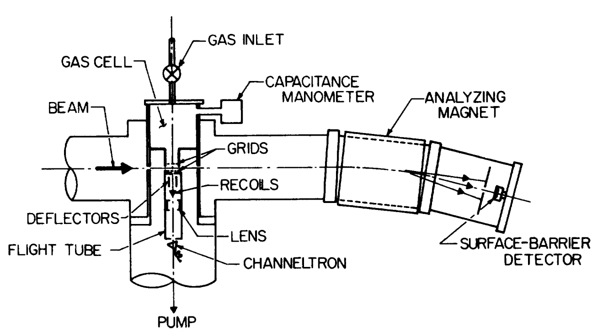

FIG. 1. A schematic representation of the experimental apparatus.

in a silicon surface-barrier detector. The flight time of the projectiles over a path length of 105 cm from the gas cell to the particle detector is ~75 ns and is constant for all charge states of the projectile. In time sequence the projectile signals are delayed electronically because of the longer flight times (1–3 μs) of the slow recoils. The postcollision projectile-charge state of interest was chosen by magnetic analysis following the collision region. A real event in the time spectrum thus designated a coincidence event and identified the value of $\sqrt{m/q}$ for the recoil as well.

The pressure at the inlet to the gas cell was measured with a capacitance manometer and was $\leq 8\times10^{-4}$ Torr at this point. The pressure at the beam is less than the inlet pressure. A second-collision charge change of the recoil within the target gas would have to occur during its 3-mm flight path to the extraction grid in order to disturb the results of the measurements. As discussed in Ref. 1, where a gas cell of geometry quite similar to ours was used, the above pressure is sufficiently low to avoid such problems. Under these conditions the recoil count rate was ~10 Hz for count rates of 3 kHz in the surface-barrier particle detector during analysis of the direct incident beam. When the magnetic analyzer was set to detect projectiles that had undergone double-electron capture, the recoil singles and surface-barrier rates were both near 1 kHz. Typical coincidence rates were 10 and 10^{-1} Hz under these two different experimental conditions, respectively.

Cross sections σ_q^{ij}, where i, j, and q denote the charge states of the incident projectile, the outgoing projectile, and the recoil, respectively, were measured. For a given projectile species, cross sections for different final projectile-charge states were placed on the same relative scale by normalizing to the number of singles recoils. This number is a measure of the product of target thickness and the number of incident ions, independent of the setting of the postcollision analysis system. The absolute cross-section scale was assigned by measuring, at constant target pressure, the number of coincident recoils per projectile ion, with the postanalysis system set on the direct beam ($i=j$), for both the heavy-ion beams and protons. The absolute cross sections for proton bombardment of Ne were taken from Pivovar and Levchenko[6] to be 0.62, 0.42 and 0.33 $\times10^{-16}$ cm^2 (q = 1) at beam energies of 1.0, 1.5, and 2.0 MeV, respectively. We note that the results so obtained appear quite consistent with those from Ref. 1. This gives us confidence in the internal consistency of this procedure. However, both sets of measurements are normalized to the results of Ref. 6. Berkner *et al.*[7] have measured the charge weighted cross section $\sum_{j,q} q\sigma_q^{6,j}$ for bare carbon nuclei at 1 MeV/amu on neon. Their value of $(16.6\pm 4.0)\times 10^{-16}$ cm^2 is slightly lower than our value of $(24.1\pm 6)\times 10^{-16}$ cm^2.

Although the charge-state purity of the incident beam was high (>99% in the desired charge state), even the small remaining impurities had significant effects on the data. The presence of these impurities was apparent in the measurement of $\sigma_q^{i(i-1)}$ and $\sigma_q^{i(i-2)}$. We direct our attention to a specific example. The recoil charge-state spectrum from F^{9+} incident and F^{8+} analyzed onto the surface-barrier detector showed clear evidence for contributions from $F^{8+}\to F^{8+}$ as well as from $F^{9+}\to F^{8+}$ interactions. It was determined that most (>90%) of the F^{8+} beam detected after magnetic analysis under these conditions was generated prior to entering the gas cell. To remove the impurity effect from our data, we measured the recoil charge-state spectrum for $F^{8+}\to F^{8+}$ and subtracted it from the spectrum for $F^{9+}\to F^{8+}$, normalizing to the number of F^{8+} ions detected. The effect of this subtraction is to remove significant fractions of the yields from recoils in charge states 1+, 2+, and 3+. For the higher-recoil charge states this correction was less than $\lesssim 5\%$. A check on this procedure is provided by the observation that the corresponding subtraction for the $F^{9+}\to F^{7+}$ case removes exactly the yield of Ne^{1+} recoils from the spectrum, as it should, since at least two electrons have been removed from the Ne in the double-electron-transfer process. For the case of $F^{9+}\to F^{7+}$, there is an additional correction to be made for contributions from contaminant F^{8+} which undergoes single capture in the target region, thus adding a small amount of the $F^{8+}\to F^{7+}$ spectrum. The size of this second-order correction, never exceeding 10%, was evaluated in a manner similar to that discussed above and subtracted from the double-capture recoil spectrum. Typical charge-state spectra for the Ne recoils are shown in Fig. 2 for $F^{9+}\to F^{9+}$, $F^{9+}\to F^{8+}$, and $F^{9+}\to F^{7+}$ cases. These spectra have undergone the subtraction process discussed above.

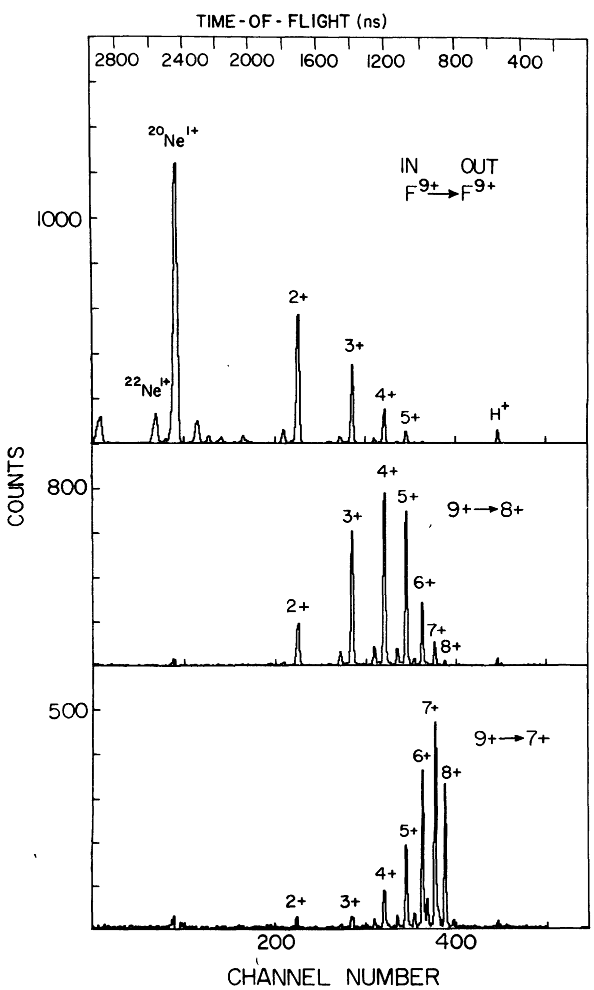

FIG. 2. Neon recoil charge-state time-of-flight spectra for 1-MeV F^{q+} ions incident on a thin Ne gas target.

III. RESULTS

The experimental total cross sections σ_q^{ij} for the production of low-velocity recoil Ne ions are given in Figs. 3 and 4 for 1-MeV/amu C, N, O, and F projectiles. These data represent the cases where the projectile either does not undergo a charge-transfer reaction during the collision $(i=j)$, captures one or two electrons in the collision $(j=i-1$ and $j=i-2)$, or, in one instance, loses a K electron $(j=i+1)$. We note that the C(6→6) and N(6→6), N(7→7) and F(7→7), and O(8→8) and F(8→8) measurements give nearly equal values for each pair of projectiles having the same input and output charge states. This feature suggests that collisions leading to the product of lower charge Ne ions occur at impact parameters sufficiently large that the projectile is fully screened by its accompanying electrons.

Total experimental production cross sections $(\sigma_q^i\equiv\sum_j\sigma_q^{ij})$ for Ne^{q+} recoils $(q=1\text{–}8)$ as functions of the incident-projectile-charge state are compared to the predictions of the Olson model[2] in Fig. 5. In this model the ionization probability of a single electron, whose binding energy is the first ionization potential of Ne, is calculated at each b by a Monte Carlo classical-trajectory

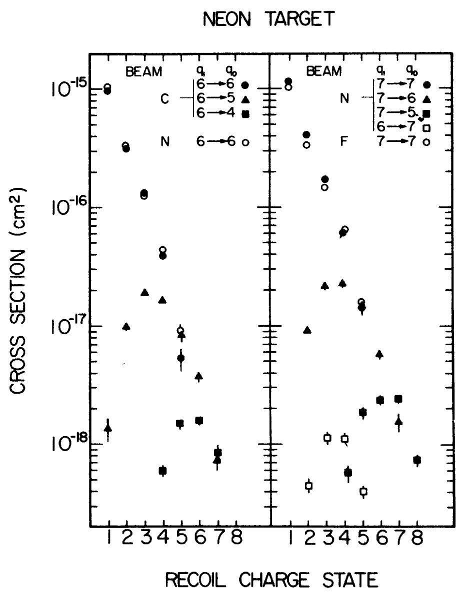

FIG. 3. Neon recoil charge-state production cross sections for 1-MeV/amu C, N, and F projectiles with incident charge state q_i and postcollision charge states $q_0 (j \equiv 0)$.

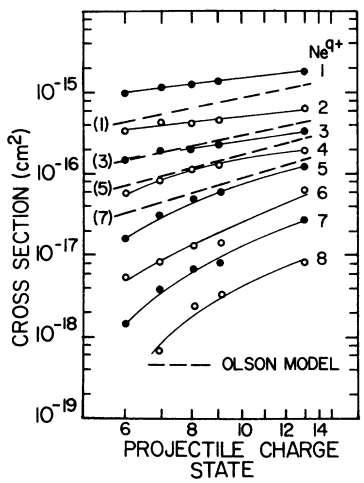

FIG. 5. Neon recoil charge-state production cross sections $\sigma_q^i = \sum_j \sigma_q^{ij}$, from the present work. The data for $q = 13$ was taken from Ref. 1. The data are compared to predictions of the Olson model (Ref. 2), with the numbers in parentheses indicating the recoil charge state for the model calculations.

method. Binomial statistics are then used to obtain the probability for multiple ionization, and the result integrated over b for the final cross section. The results of the model are given as the dashed lines for 1+, 3+, 5+, and 7+ charge states of Ne in Fig. 5. The data for projectile-charge state 13+ is taken from Cocke.[1] The model gives the general trends of the data for the low Ne^{q+} charge states ($q \lesssim 3$) with agreement between data and calculation being within experimental error for $q = 3$. However, for the higher charge states of Ne this model overpredicts the production cross section by factors of ~2.5 and 10 for the Ne^{5+} and Ne^{7+} charge states, respectively. The failure of the model to predict the higher-recoil charge-state cross sections was noted earlier,[1] and attributed to the failure of the model to take into account the increase in ionization potential of the neon with increasing ionization state.

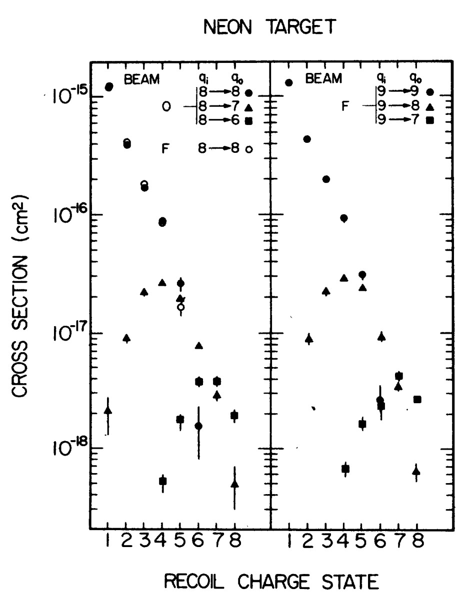

FIG. 4. Neon recoil charge-state production cross sections for 1-MeV/amu O and F projectiles with incident charge states q_i and postcollision charge states $q_0 (j \equiv 0)$.

In the ED model,[1] the energy transferred to the target electrons, at each b, is calculated assuming a classical collision with free electrons initially at rest. The subsequent ionization state attained by the excited target is then obtained from the statistical analysis of Russek and Meli.[4] The ED calculations for recoil charge states 1+, 3+, 5+, and 7+ are compared to the recoil Ne data as functions of the incident-projectile charge in Fig. 6. The consistent overestimation of the single ionization cross section is in agreement with earlier findings by Cocke[1] and may reflect the failure of the impulse approximation coupled with the feature that much of the single ionization cross section comes from impact parameters where the energy transfer per L electron is considerably below the energy required to excite the closed shell target. The model results for the Ne^{3+} and Ne^{5+} charge states are in fair agree-

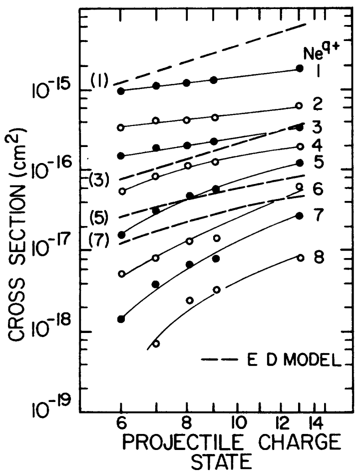

FIG. 6. Neon recoil charge-state productions cross sections $\sigma_q^i = \sum_j \sigma_q^{ij}$, from the present work. The data for $q=13$ was taken from Ref. 1. The data are compared to predictions of the ED model (Ref. 1), with the numbers in parentheses indicating the recoil charge state for the model calculations.

ment with the measurements. For recoil charges 6+ –8+, this model also predicts much higher cross sections than are observed. We do not know whether this is due to an overestimation of the electronic energy transfer by the simple classical model or reflects a fundamental failure of the statistical treatment of the process.

The observation that collisions which change the projectile-charge state generate higher charged recoils than those which do not, requires a more detailed treatment of the collision process in which some correlation between projectile and target charge change is introduced. One might imagine that at least part of the correlation occurs because charge capture by the projectile necessarily requires complimentary electron loss by the target. However, the data show the shift in the recoil charge spectrum to be much more than the number of electrons captured. Further, the shift accompanying single-electron capture is nearly the same as that for single loss from the projectile. We are thus led to suggest that the primary source of correlation enters through the impact-parameter dependences of the target and projectile-charge-changing processes. In order to investigate whether this conjecture is reasonable, we have tried to describe our data with a simple factorization model. We propose a representation of the overall probability [$P_q^{ij}(b)$ where our indexing is the same as that used for the total cross sections] as a product of probabilities for charge change of each collision partner. That is, we write the probability as $P_q^{ij}(b) = P_q^i(b) P_{ij}(b)$. Here $P_q^i(b)$ is the probability of generating recoil charge state q, independent of what happens to the projectile, and $P_{ij}(b)$ is the probability of the projectile going from charge state i to j, independent of what may simultaneously happen to the recoil. The observed cross sections $\sigma_q^i (\equiv 2\pi \int P_q^i(n) b db)$, while not uniquely determining the functions $P_q^i(b)$, place strong constraints on them. The approach we have used to obtain these functions is to use the ED-model prescription with the added modification of multiplying the energy transfer in that model by a b-dependent factor which reduces the energy transfer at small b. Using this procedure it was possible to find a "fit" to the observed values of σ_q^i which reproduced the data to within 30% for $1 < q < 7$, the region of major importance in this discussion. The values of $P_q^i(b)$ from this adjusted model were then employed in the factorization procedure.

We limit our discussion to those cases where the projectile is either the bare nucleus or hydrogenlike prior to the collision. In order to work analytically with $P_{ij}(b)$, we assume it to have the Gaussian form $P_{ij}(b) = P_0^{ij} \exp[-(b/r_{ij})^2]$. We remind the reader that i and j specify the initial and final charge states of the projectile. The probability at $b=0$ is P_0^{ij} and r_{ij} is a radius parameter. In using the ED model to calculate $P_q^i(b)$ for the case of single capture, the capture was presumed to be accompanied by energy loss to a

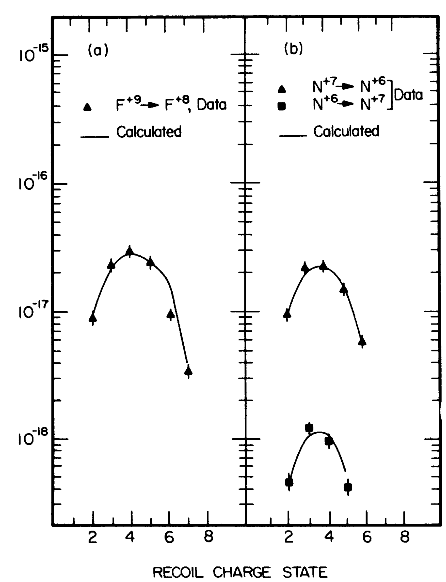

FIG. 7. (a) Neon recoil production cross sections for incident 1-MeV/amu F^{9+} ions have undergone electron capture in the collision. The calculated curve is based upon Eq. (1). (b) Neon recoil production cross sections for incident 1-MeV/amu Ne^{7+} and Ne^{6+} ions which have undergone electron capture or ionization, respectively, during the collision. The calculated curves are based upon Eq. (1).

TABLE I. Model calculations for the cross sections and total projectile-charge-changing cross sections.

Projectile Incident (i)	Exit (j)	P_0^{ij}	r_{ij} (10^{-8} cm)	σ_{ij} (present) [a] (10^{-18} cm^2)	σ_{ij}(other) (10^{-18} cm^2)
F^{+9}	F^{+8}	0.75	0.70	115.4	155 [b]
N^{+7}	N^{+6}	0.70	0.60	79.2	75 [b]
N^{+6}	N^{+7}	0.046	0.50	3.6	3.0 [c] 1.5±0.3 [d]

[a] From $\sigma_{ij} = \sum_q \sigma_q^{ij}$.
[b] OBK multiplied by 0.3, capture from target L shell to all projectile shells (Ref. 10).
[c] Reference 12.
[d] Reference 13.

singly ionized, rather than neutral, target (see Ref. 1). We thus proceed to calculate

$$\sigma_q^{ij} = 2\pi \int P_q^i(b) P_{ij}(b) b\, db\ . \qquad (1)$$

The effect of this modification to the original ED calculation is to limit the range of impact parameters contributing to the final charge-state distributions of the low-velocity recoils because of the dominance of smaller impact-parameter contributions in the projectile-charge-changing collisions.

Calculations using Eq. (1) are compared to data for F(9→8), and N(7→6) and N(6→7), in Figs. 7(a) and 7(b), respectively. The parameters P_0^{ij} and r_{ij}, which were adjusted to obtain satisfactory fits to the data, are given in Table I. Cross sections for the production of Ne recoils in charge states $q = 3-7$ are reproduced by the model calculations. The values of r_{ij} in Table I are substantially larger than the K-shell radii of the F and N projectiles. This is no surprise for the case of single capture, since much of the capture is expected to come from the target L shell. For the case of single ionization of the hydrogenlike nitrogen system, it might seem surprising at first glance that r_{ij} is so large. However, recent results by Hagmann *et al.*[8] for direct measurements of the impact-parameter dependence of Ne K-shell ionization by F in the ~0.5-MeV/amu range indicate that K-electron removal in such symmetric collisions takes place substantially outside the K-shell radii, in qualitative agreement with our conclusions. Further, results by Randall *et al.*[9] for direct measurements of the impact dependence of K-shell ionization cross sections as a function of Z_1/Z_2 have established that the scale lengths of $P(b)$ are increasing rapidly beyond the target K-shell radius as the symmetric collision system is approached.

Also included in Table I are the experimental total cross sections for projectile-charge change $\sigma_{ij} = \sum_q \sigma_q^{ij}$. In the case of the charge-exchange reactions $F^{9+} \to F^{8+}$ and $N^{7+} \to N^{6+}$, these cross sections are compared to scaled[10] calculations of the total charge-exchange calculations using the Oppenheimer-Brinkman-Kramers (OBK) approximation[11] for transfer of a target electron to all shells of the projectile. The present cross sections agree with the calculated charge-transfer cross sections within a factor of 2. Woods *et al.*[12] have measured K-ionization cross sections for F-Ne collisions over an energy range comparable to that of the present work. Their measurement of 3.0×10^{-18} cm^2 at 0.8 MeV/amu for F K-shell ionization is in reasonable agreement with our single loss cross section in N, $\sigma_{76} = 3.6\times10^{-18}$ cm^2, calculated from P_0^{ij} and r_{ij}. Recent measurements by Dillingham and Macdonald[13] for electron loss, $N^{6+} \to N^{7+}$, for N ions in collision with Ne are somewhat lower than ours.

IV. CONCLUSIONS

The present work shows, for those collisions between highly charged fast heavy ions and neutral gas target atoms where the projectile does not undergo a charge change, that the ED and Olson models predict reasonable cross sections for the production of recoils with $q < 6+$. Collisions in which the projectile-charge changes, result in recoil charge-state spectra strongly enriched in the highly ionized species. We conjecture that this is due primarily to the preselection of an impact-parameter region by the projectile-charge-changing event, and have presented a model to suggest what impact-parameter ranges are important.

ACKNOWLEDGMENTS

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