Measurements of Recoil Ion Longitudinal Momentum Transfer in Multiply Ionizing Collisions of Fast Heavy Ions with Multielectron Targets

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The longitudinal momentum transfer to the recoil ion in collisions of 1 MeV/amu bare F ions with Ne are resolved for final charge states of both projectile and recoil ions. We observe the recoil to be thrown backwards in electron-capture events, reflecting the physical impact of the electron translation factor. The size of the momentum transfer is in agreement with classical trajectory Monte Carlo calculations for low charge state recoil ions but not for high charge state recoil ions.

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When a fast bare heavy ion passes through a multielectron atom at speeds greater than those of the outer target electrons, it may capture one or more electrons while at the same time ejecting several electrons into the continuum. Understanding the complex exchanges of energy and momentum among the components of the collision system is important to any full understanding of the energy loss and transverse scattering processes which determine the way in which fast ions interact with matter. Such interactions are seen in a wide range of applications involving ion beams traveling into tissue and materials and are commonly discussed in terms of the study of stopping powers and angular scattering distributions which average over many initial charge states and reaction channels. In spite of the long and venerable history of the study of these average quantities, the underlying process, namely, the collision of a fast heavy ion in a well-defined charge state with a single target atom, is sufficiently complex that no comprehensive description of the energy and momentum transfer is at hand. A major goal of this study is to provide new insights into this binary collision process. We report here the first direct experimental measurements of the longitudinal momentum transfer to the recoil ion for fast heavy ion–atom collisions. We have made the first experimental observations of the backwards recoil of the target ion, which is caused by the transfer of electrons from one center to the other and reflects the physical impact of the well known electron translation factor. From our results, we deduce that the process may be viewed as a two-body-like electron-capture process embedded within a multielectron ionization collision between the projectile ion and the target electrons.

Recoil ion momentum spectroscopy has been widely used in recent years to provide information on the overall distribution of the momentum transfers among the final projectile, recoil, and continuum electrons [1–8]. Information of this type supplements time-honored electron spectroscopy [9] by allowing the selection of final projectile and recoil ion charge state combinations, thus permitting the selection of any impact parameter range from very soft to very hard collisions. Previous measurements of recoil momentum spectra have been limited to the measurements of the transverse component of the recoil momentum. Since this component has received a major contribution from the Coulomb repulsion between nuclei, it is roughly correlated with the impact parameter of the collision. Departures from two-body kinematics between projectile and recoil ions can only be caused by the removal of transverse momentum by electrons ionized to the continuum. Experiments have shown that for hard collisions this latter contribution is relatively small, while for soft collisions the continuum electrons may carry away an important fraction of the transverse momentum transferred from the projectile [1,5–7]. The only theoretical calculations which have been able to treat these complex collisions are the *n* CTMC (classical trajectory Monte Carlo) calculations of Olson [10] and those of Horbatch [11].

The longitudinal momentum transfer (p_z), which is the subject of this paper, is closely related to the energy exchange between collision partners. The only previous experimental work on the recoil longitudinal momentum transfer is the pioneering work of Lepera *et al.* [12], who measured angular distributions of recoil ions in Cl-Ne collisions, but they were not able to directly deduce longitudinal momentum transfers. Projectile energy loss measurements, from which longitudinal momentum transfers can be deduced, have been reported by Schuch *et al.* [13] and Shöne [14] for 0.8 MeV/amu C on Ne. If two-body kinematics between projectile and recoil ions were to hold, these energy losses would lead to the prediction that the recoil ions should be thrown slightly forward 90° to the beam. If this result were true, however, it would imply that the longitudinal momentum carried away from the collision by the continuum electrons is negligible, a conjecture not previously tested experimentally. A major conclusion of the present paper is that this conjecture is incorrect and that the use of two-body kinematics to describe the longitudinal momentum and energy exchange between projectile and recoil is unjustified. Our results show the signature of two-body kinematics in the

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electron-capture process, but this capture can be accompanied by the ejection into the target continuum of several target electrons which carry away the main share of the longitudinal momentum lost by the projectile. To this part of the process the recoil ion is apparently largely a spectator.

The experiment was performed at the KSU tandem Van de Graaff accelerator with the apparatus shown in Fig. 1. A tightly collimated beam of 19 MeV F ions crossed a gas jet, which was collimated with a glass capillary array. After passing through the collision region, the projectile beam was charge state analyzed and struck the face of a two-dimensional position sensitive channel plate detector located 5.2 m downstream. The recoil ions were extracted by a very uniform transverse electric field and projected onto the face of a second 2D detector where they were detected in time coincidence with the projectile ions.

Referring to the coordinate system in Fig. 1, the y and z components of the recoil momentum could be determined by the time-of-flight of the recoil ion and its position on the detector, while the x component could be determined from the time difference between the center of a particular recoil charge state's time-of-flight distribution and the actual time for a particular event. The resolution of the system in the z direction, the important direction for this paper, was dominated by the thermal motion in the target and corresponded to 11 a.u. (FWHM) in p_z. Contributions to the p_z distributions from multiple collision events were evaluated and subtracted, and points for which the correction was large were omitted from all data presented here. Care was taken to eliminate stray magnetic fields and to ensure a uniform electric field in the interaction region. Further details of the experiment will be given in a forthcoming publication.

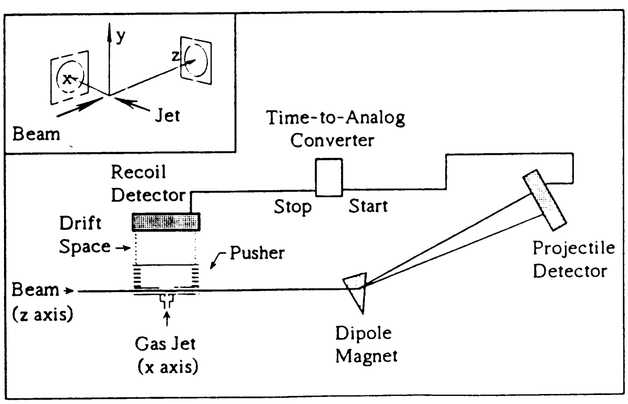

FIG. 1. Schematic of apparatus. The recoil ion detector was a 40 mm diam two-dimensional position-sensitive channel plate detector containing a resistive anode. The projectile detector was similar, but contained a backgammon (wedge and strip) anode. The inset shows the coordinate system used in this paper.

The left side of Fig. 2 shows the positions of the recoil ions on the recoil detector for selected cases. These correspond to the projections of the recoil momentum distributions in the z-y plane. Below a recoil charge state (q) of about 2, the z and y momentum distributions show only the resolution function, but for higher q the true distributions emerge to show that the transverse momentum (y) component is generally much larger than the longitudinal (z) component. The recoil ion longitudinal momentum spectra, formed by transforming each (z,y) event in real space into momentum space and projecting the resulting spectrum onto the z axis, are shown in the right-hand parts of this figure. While the widths of these spectra are large and nearly constant, an increasing shift in the mean value of p_z is seen as one proceeds from soft collisions involving no electron transfer to harder ones involving multielectron transfer. The shift is in the backwards direction.

It is readily apparent from Fig. 2 that the longitudinal shifts in the recoil ion position spectra are very small. Nevertheless, reliable mean shifts could be determined, since data for all recoil charge states were collected simultaneously, eliminating many potential sources of systematic error. In addition, we usually placed two ad-

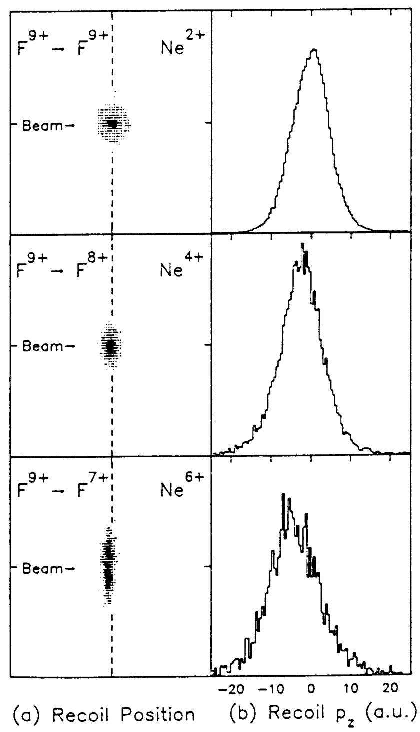

FIG. 2. (a) Two-dimensional position spectra from the recoil detector for selected cases. The transverse momentum transfer distribution is seen in the y direction, the longitudinal transfer in the z direction. The center of the distribution, corresponding to a 90 deg exit angle for the recoil, is indicated by the line. (b) Longitudinal momentum transfer spectra for these cases obtained by event-by-event processing for the data in (a) and projection onto the z axis.

jacent projectile charge states on the projectile detector at the same time, so that data for different projectile charge states could be connected within a single data run. Reproducible shifts were observed in each of four data sets, gathered many months apart.

In Fig. 3 we show the mean value of p_z for all measured final charge state combinations, plotted as a function of the number of electrons captured by the projectile ion. We consider to what extent this many-body collision might behave as a two-body collision involving the transfer of n electrons from the target to a projectile moving at velocity v. Conservation of momentum and energy leads to the relationship [15]

$$p_z = -\frac{Q}{v} - \frac{n m_e v}{2} - p_e\,, \tag{1}$$

where m_e is the electron mass, p_e is the net momentum carried off by ionized electrons, and Q is the electronic energy in the initial state minus that in the final state, so that Q is positive for exoergic reactions. The condition $p_e = 0$ corresponds to the two-body collision case. This expression is valid if the scattering angle is small, and if the recoil kinetic energy and Q value are much smaller than the projectile kinetic energy (conditions well satisfied here). Figure 3 shows that the experimental value of p_z becomes increasingly negative with increasing n, in agreement with the second term of Eq. (1), with a slope only slightly smaller than the $v/2$ which one would expect from this equation. The corresponding CTMC result shown in the lower part of Fig. 3 displays this trend even more strongly. Thus, in the charge exchange reaction, the recoil momentum from electron mass transfer from target to projectile centers is displayed for the first time. The statistical error in the CTMC calculation is final-state dependent, being larger for triple-capture and high recoil charge states, but not exceeding 0.5 a.u.

In Fig. 4 we show the data plotted versus recoil charge state. We concentrate our attention first on direct ionization, for which the projectile charge state does not change. For the C^{+6}-Ne system at 0.8 MeV/nucleons described by Schuch *et al.* [13] and Schöne [14], the projectile energy loss for direct ionization increases by 1 keV in going from $q=1$ to 6. If similar inelasticities were to hold for the present case, Eq. (1) would predict an increase in the recoil p_z of $+6$ a.u. in going from $q=1$ to 6. Our experimental results in Fig. 4 show no such trend, and indeed show p_z to be almost independent of q, in near agreement with the CTMC prediction. Our interpretation of this result is that the Q/v term in Eq. (1) is nearly perfectly balanced by p_e. The physical picture which emerges for this channel is that the primary ionization interaction is between projectile and electrons, and that the recoil "core" which remains is nearly a spectator to the ionization process.

For electron-capture events, the situation is more complex. While the CTMC and experiment agree for low q, for q of 6 and above the CTMC prediction goes counter to the experimental trend. We can only speculate on the reason for this disagreement. The total cross section for the production of charge states of 6 and higher is 1.25×10^{-17} cm^2 [16], very similar to that of 0.75 $\times10^{-17}$ cm^2 which can be deduced from the data of Woods *et al.* [17] for K to K transfer in such collisions. Thus the production of charge states 6 and higher are very likely to occur in an impact parameter range where the probability for target K-shell electron removal is of order unity [18]. If the same final states were formed regardless of the origin of the electron, the capture of a K electron would, from the first term on the right-hand side of Eq. (1), throw the recoil ion forward by about 6 a.u.

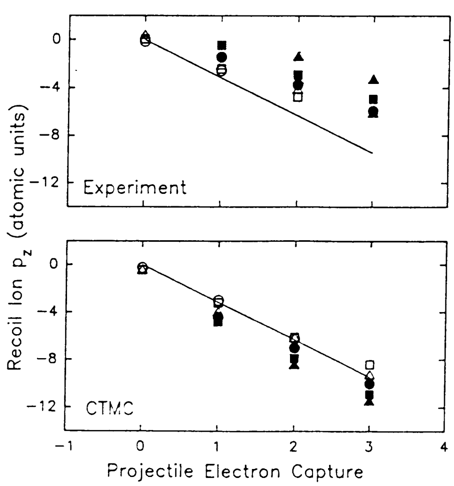

FIG. 3. Mean values of p_z plotted versus n, the number of electrons captured and kept by the projectile. The upper half of the figure shows the present experimental results, the lower half, the CTMC results.

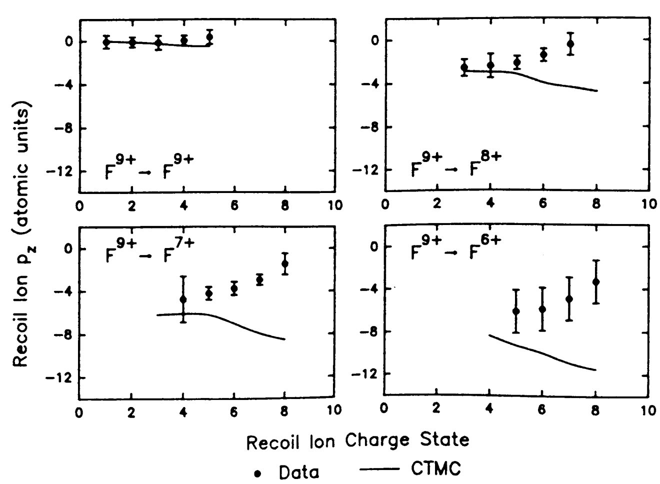

FIG. 4. Mean values of p_z plotted versus recoil charge state q. The initial and final projectile charge states are indicated in each figure. The data points are the present experimental results, and the line, the CTMC results.

more than the capture of an L electron, similar to what is observed for the last three charge states. In principle, this effect is included in the CTMC calculation, which includes target K electrons, but the CTMC treatment may not be adequate in a region where such strong MO promotion mechanisms are known to be in effect.

We point out that, for simplicity and because quantitative evaluation is very difficult to make, we have ignored in the previous discussion effects which postcollision Auger emission would have on projectile and recoil charge states. Such decays in the projectile ion would shift counts from double- (and higher-) capture channels toward lower apparent capture channels (lower n), and would worsen agreement between CTMC and experiment. However, highly (multiply) excited target ions might be created. A large target excitation would lower p_z by increasing the endoergicity $(-Q)$, and subsequent isotropic emission of Auger electrons would result in a high recoil charge state without contributing to p_z. The present comparison of the data with the CTMC results does not take this possibility into account, and such a process may be a significant cause of the discrepancy seen in Fig. 4.

In conclusion, measurements of the longitudinal momentum transfer to the recoil ion in multiply ionizing fast collisions between bare F ions and Ne indicate that the p_z to the recoil is typically extremely small, smaller than what one would expect from two-body kinematics between projectile and target. In contrast to the transverse momentum case where the Coulomb repulsion of the nuclei is dominant, the nucleus-nucleus interaction makes no contribution to the longitudinal momentum transfer to the recoil ion, and thus the proportion of momentum carried by the continuum electrons is relatively much greater in the longitudinal direction than in the transverse one. The picture of the reaction which emerges is that of a capture event for which two-body kinematics holds, embedded within a background of ionizing interactions between the projectile and target electrons in which the major part of the p_z lost by the projectile is absorbed by the continuum electrons, and the recoil core is nearly a spectator to this part of the collision. Agreement between CTMC and experiment is good for charge states below about 6, but increasing discrepancies appear for higher q, for which no clear explanation is presently at hand. The failure of two-body kinematics makes it clear that the use of longitudinal momentum spectroscopy as a tool for the determination of inelasticities is limited to cases for which no target continuum electrons are generated in the primary collision process.

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