PHYSICAL REVIEW A VOLUME 36, NUMBER 4 AUGUST 15, 1987

Steep dependence of recoil-ion energy on coincident projectile and target ionization in swift ion-atom collisions

J. C. Levin, R. T. Short, C.-S. O, H. Cederquist, S. B. Elston, J. P. Gibbons, and I. A. Sellin
Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200
and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6377

H. Schmidt-Böcking
University of Frankfurt, Frankfurt, Federal Republic of Germany
(Received 25 February 1987)

The first measurements of the mean energies E_r of highly charged recoil ions detected in coincidence with multiply ionized swift projectiles are reported. Beams of 23-, 27.6-, and 33-MeV Cl^{5+} produced Ar recoil ions whose mean energies exhibited a strong dependence on the product (qr) of final projectile and recoil charge states. For large qr values, E_r is substantially larger than earlier estimates, and allows inference of characteristic impact parameters without requiring measurements of projectile scattering angle.

In the past decade, the production of low-energy high-charge-state recoil ions by swift, heavy-ion impact has been effectively exploited. Low-emittance recoil-ion sources have been used to provide spectroscopic sources of low Doppler spread, as well as to produce secondary beams for slow ion-atom collision experiments.[1] The "ion-hammer" technique has proven a rich source of novel data on ion-atom collision phenomena, particularly on single- and multiple-electron capture in the 0.1-to-few keV per charge energy range.[1] The possibility of producing a powerful, parasitic source of bare and few-electron low-energy ions (greater than 10^{12} extracted ions/sec), "hammered" at MHz frequencies in a heavy-ion storage ring, has been conjectured by Ullrich *et al.*[2]

Despite the abundance of activity in the field[3] and the importance of the parasitic-ion-source possibility, few data concerning the energies and angular distributions of the primary recoil ions have been published.[4] Ullrich *et al.*[5] have recently published a measurement of the entire recoil-energy distribution for Ne^{3+} ions produced by 1.4-Mev/u U projectiles, using a specially designed time-of-flight (TOF) spectrometer. Substantial new knowledge of intrinsic interest, as well as practical significance for design of parasitic sources, can be gained from measurements of recoil energies and angular distributions.

This paper concerns the first quantitative measurements of the mean energies E_r of slow, highly charged recoil ions produced in MeV/u collisions as a function of recoil-ion charge state r and emergent projectile charge state q. For high (q,r) values, E_r is found to be several times *larger* than suggested by earlier estimates (made for more restrictive assumptions than apply here.[2,6] The steep dependence of E_r on q and r observed permits inference of a characteristic impact parameter $\bar{b}$ corresponding to the mean recoil energy for each (q,r) pair. This method thus augments difficult measurements of projectile scattering angle in coincidence with one or more reaction fragments, a method primarily useful for harder collisions and often requiring angular resolution of ~ 100 μrad. Since calculated target ionization transition probabilities are not sharply peaked in b, but typically extend over a range comparable[6] to b, one expects the recoil ions to be spread over a corresponding range in E_r and recoil angle. Present measurements are of mean recoil energies and thus indicate $\bar{b}$, but not its range.

The measurements were performed using a TOF method[1] already demonstrated[7] (in "x-ray scalpel" studies of high-r recoil production) to have sufficient resolution to measure energies of recoils as low as less than 0.04 eV to an accuracy of approximately 0.02 eV. Errors in the present experiment are larger because of the greater jitter in position of the steered charged-particle beam. Since E_r values for high-charge-state recoil ions produced by charged-particle impact can be approximately two orders of magnitude higher, the method's intrinsic accuracy can improve significantly on upper limits set in all previous hammer experiments. In this experiment, beams of 23-, 27.6-, and 33-MeV Cl^{5+} ions from the Oak Ridge National Laboratory (ORNL) EN Tandem Facility collimated to less than 1 mm diameter were used to produce Ar recoil ions in a dilute gas target (less than 1 mTorr) maintained in the extraction region at the front end of the analyzer. This target was viewed by the horizontally mounted TOF analyzer through a 3-mm-diameter hole located adjacent to the projectile beam. Projectiles were detected by a University of Frankfurt position-sensitive parallel-plate avalanche detector (PPAD) following dispersion of scattered projectile ions by an electrostatic charge sorter. Recoil TOF pulses started a time-to-amplitude converter (TAC), and pulses registered by the PPAD, suitably delayed, stopped the TAC. Further details concerning analyzer resolution, performance, and use are discussed in Refs. 1 and 7.

An example of a TOF spectrum is shown in Fig. 1(a). Mean recoil energies for $r=4-9$ were determined for $q=6-8$ through study of the widths of the corresponding TOF peaks, using procedures similar to those described in

Ref. 7. For each r the mean initial energy U_0 was deduced from a fit of the full widths at half maximum (FWHM) to the form

$$\Delta t^2 = \alpha + \beta/(r\kappa) + \gamma/(r\kappa)^2 \ . \quad (1)$$

The constants α, β, γ represent contributions to flight time from, respectively, timing uncertainty; flight-time variations due to field fringing; and recoil-ion energy.[7,8] The electric field scaling parameter (κ) represents six different choices of proportionately scaled[7,8] values of electric fields in the TOF analyzer. The essential correctness of the ansatz for Δt^2 was again[7] well verified by the clustering of TOF data around fitted quadratic curves [Fig. 1(b)]. Strictly, the contribution to flight time associated with the motion parallel to the spectrometer axis was observed.

The r distributions for one-, two-, and three-electron loss are not representative of total recoil-ion-production cross sections which peak at $r=1$; both are shifted toward higher r. The spectrum corresponding to coincident three-electron loss [Fig. 1(a)] maximizes at $r=6$ and exhibits wider peaks than the one-electron-loss spectrum for which $r=3$ is dominant. This shift to large r can be attributed to harder collisions involving smaller b, since for reasons of wave-function-overlap multiple-electron loss is undoubtedly more probable at smaller b than are direct ionization and single loss. Similar shifts in r, also attributed to b dependence, were observed in measurements of Ar^{r+} recoil-ion spectra in coincidence with single-, double-, and triple-electron capture[9] by 1.4-MeV/u Fe^{15+}.

Figure 2 and Table I show that the dependence of E_r on the number of electrons lost is very steep. The errors quoted are statistical and represent one standard devia-

TABLE I. E_r and $\bar{b}$ for Ar^{r+} recoil ions detected in coincidence with Cl^{q+} for Cl^{5+} energies of 23 and 27.6 MeV.

			23 MeV		27.6 MeV	
qr	r	q	E_r (eV)	b (a.u.)	E_r (eV)	b (a.u.)
40	5	8	0.41(12)	0.55	0.21(09)	0.61
42	7	6	<0.3	>0.60	<0.3	>0.59
	6	7	0.27(15)	0.64	<0.2	>0.67
48	8	6	0.46(42)	0.57	0.40(35)	0.56
	6	8	0.63(12)	0.54	0.35(12)	0.58
49	7	7	0.42(16)	0.58	<0.4	>0.6
56	8	7	0.84(24)	0.50	0.47(28)	0.55
	7	8	1.14(25)	0.48	0.71(21)	0.50
63	9	7	2.08(50)	0.42	1.66(54)	0.42
64	8	8	2.26(35)	0.41	1.43(34)	0.43
72	9	8	4.20(76)	0.35	2.74(78)	0.37

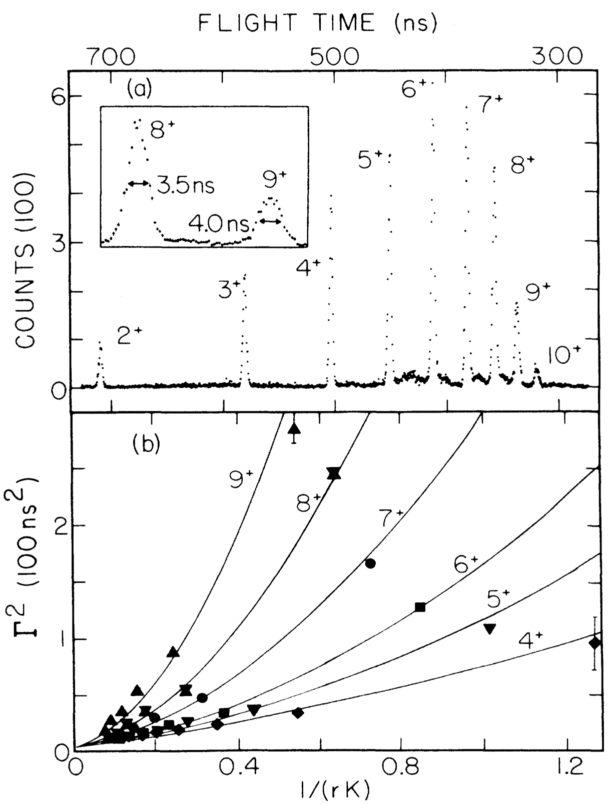

FIG. 1. (a) Spectrum of Ar^{r+} recoil ions produced by 23-MeV Cl^{5+} and detected in coincidence with Cl^{8+}. Inset shows FWHM Γ of Ar^{8+}, Ar^{9+}. (b) Quadratic behavior of the square of Ar^{r+} TOF peak widths plotted as a function of $(r\kappa)^{-1}$ (see text).

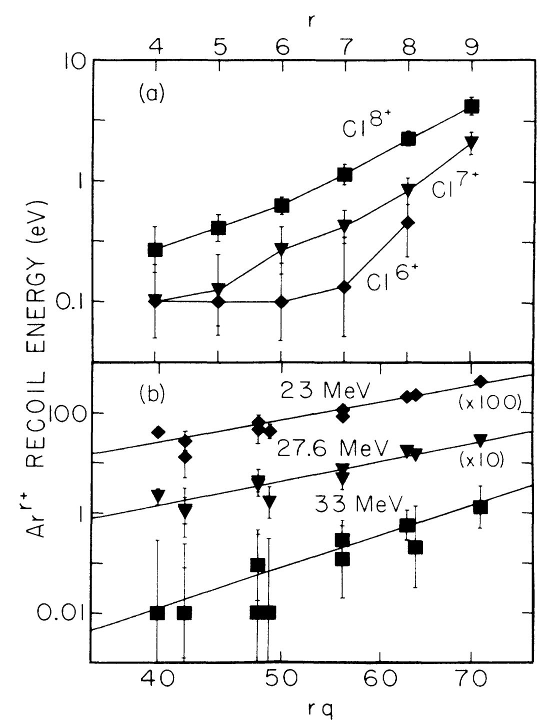

FIG. 2. (a) Dependence of E_r on product (qr) of final projectile and recoil charge states for one-, two-, and three-electron loss from 23-MeV Cl^{5+} projectiles ions. (b) E_r vs qr for beams of 23-, 27.6-, and 33-MeV Cl^{5+}. Data have been fitted to straight lines (see text), both shifted for clarity. Both scales are logarithmic.

tion. The rapid variation observed offers the possibility of relatively sharp definition of $\bar{b}$ for successive losses of one, two, or three electrons in projectile ionization events coincident with ionization of r target electrons. To realize this possibility, a model connecting E_r and b is needed.

Olson used a classical trajectory Monte Carlo (CTMC) method[6] to calculate inelastic multiple ionization cross sections for 1-MeV/u collisions of bare ions ($q=2-20,44$) with the rare gases. Assuming a projectile velocity appreciably greater than that of the target electrons (not the case here), Olson's parametrization of the CTMC results led to an expression for recoil energy as a function of impact parameter

$$E_r \text{ (in eV) } \cong 4\times 10^{-4} q^2 r^2/(M_T E_P b^2) , \tag{2}$$

with M_T the target mass in u, E_P the projectile energy in MeV/u, and b in units of a_0 (Fig. 3). Although this formula was derived using calculated probability distributions $P(b)$ for producing ions of each r, the same dependence is also obtained for elastic Coulomb scattering, except for a factor $\gtrsim 2$ Olson attributed to the approximately half-collision nature of the interaction (the target is neutral on the incoming half).

Though in reality we deal here with a complex many-body problem, two-body kinematics provides a useful guide since electron-to-nucleus mass ratios are of order parts in 10^5. We have therefore sought to relate E_r to b through a screened elastic Coulomb scattering calculation in which the center-of-mass projectile scattering angle is determined by evaluating the deflection function[10] for two half-collisions,

$$\Theta_{\text{c.m.}} = \pi - b \sum_{i=1}^{2} \int_{\rho_0}^{\infty} \frac{dr}{r^2 \left[1 - \frac{b^2}{r^2} - \frac{V_i(r)}{E_{\text{c.m.}}} \right]^{1/2}} . \tag{3}$$

All projectile and target ionization is thus assumed to occur at the distance of closest approach ρ_0. The interatomic potential V_1 is approximated by the potential of the bare target and projectile nuclei, reduced as a function of separation ρ by the universal screening function of Ziegler,[11] who obtained this function by fitting a sum of four decaying exponentials to a representative group of 522 pairs of calculated interatomic potentials. The potential V_2 is the greater of the potentials V_1, and the unscreened Coulomb potential for the asymptotic charges q,r. After removal of the singularity, Eq. (3) was integrated by 96-point Gauss-Legendre quadrature using tabulated abscissas and weights.

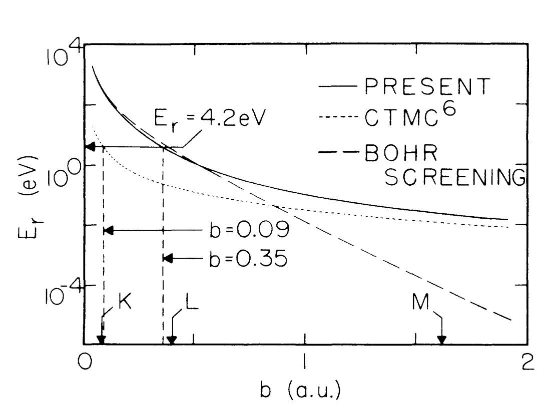

FIG. 3. Ar^{9+} recoil energies as a function of impact parameter for 23-MeV $Cl^{5+} + Ar \rightarrow Cl^{8+} + Ar^{9+}$ for the present calculation (see text), a CTMC model (Ref. 6), and Bohr screening. Indicated are the measured recoil energy, corresponding impact parameters, and Hartree-Fock expectation values of neutral Ar K, L, and M shells.

Application of two-body energy-momentum conservation then permits E_r to be calculated as a function of $\Theta_{\text{c.m.}}$ and hence b. The values of b implied by the measured values of E_r are tabulated in Table I as a function of qr and illustrated in Fig. 3, as are comparative values of the Hartree-Fock radial expectation values for electrons in the shells being ionized. Within errors, E_r and $\bar{b}$ are seen from Table I to be largely independent of q and r for a given qr.

In our model $E_r \cong 4.2$ eV measured for $(q,r)=(8,9)$ corresponds to $\bar{b}=0.35$ a.u. Since this final state can only be formed by ionization from the $n=2$ shells of both target and projectile, the excellent agreement with the Hartree-Fock L-shell neutral target expectation value 0.38 a.u. is very satisfying. The unrealistically small b (0.09 a.u.) implied by Eq. (2) may be ascribed to the sudden collision conditions assumed in the CTMC calculations not being met, to the use therein of screened Z's picked to optimize radial expectation values of the active electrons rather than the description of the internuclear motion, and to influence of interactions between overlapping projectile and target electron clouds (Pauli excitation). Better agreement with our experiment results from assuming that *effective charges seen by the target and projectile nuclei at the moment of closest approach are of much greater importance in determining E_r than the asymptotic values* (q,r). Using effective target and projectile charges of 12.6, 11.9, respectively, obtained from our Hartree-Fock calculations for $(q,r)=(8,9)$, Eq. (2) yields a recoil energy of 2.8 eV at $b=0.35$ a.u., in much better agreement with our measurement.

In Fig. 2(b) it is interesting to note clustering of E_r values about curves of E_r versus the product qr. To the extent there is a one-to-one correspondence between the product of the instantaneous screened charges developed at the moment of closest approach and the asymptotic product qr, either may be chosen as a *key* (and physically very reasonable) parameter determining E_r. The approximately linear behavior of $\log(E_r)$ on $\log(qr)$ suggests a power-law dependence in which $E_r \propto (qr)^n$ where least-squares fit results give $n \approx 5$. This strong dependence, far steeper than the $n=2$ implied by Eq. (2), demonstrates the relevance of the factors just discussed.

We have thus demonstrated a method for determining mean recoil energies of low-energy ions produced in swift ion-atom collisions, without requiring $\lesssim 100$ μrad projectile scattering-angle resolution. We find that for sufficiently high qr, the *recoil energies can easily exceed estimates similar to Eq. (2) by greater than or approximately equal to an order of magnitude.* Thus for high qr

values, greater care will be needed in designing parasitic ion sources than evident heretofore. Since our measurements average over the broad $P(b)$ distribution associated with each q,r pair, future E_r measurements made in coincidence with projectile scattering angle and charge state offer an opportunity to explore the b dependence of E_r in greater differential detail. Angle-resolved determinations of E_r would also be most worthwhile. Calculation shows that over the ranges of concern here E_r is sensitive to b but not reaction Q value, whereas recoil angle is very sensitive to Q. Understanding multiple ionization at a still more fundamental level, through further exploration of these complementary dependences, is therefore highly desirable and believed feasible.

We are grateful to Joachim Burgdörfer for useful discussions. This work was supported in part by the National Science Foundation, by Deutsche Forschungsgemeinschaft, and by the U.S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

[1]For recent reviews see L. Liljeby *et al.*, Phys. Scr. **33**, 310 (1986); S. Kelbch *et al.*, J. Phys. B **18**, 323 (1985); Proceedings of an International Symposium on Production and Physics of Highly Charged Ions, edited by L. Liljeby [Phys. Scr. **T3**, 5 (1983)].

[2]J. Ullrich *et al.*, J. Phys. B **17**, L785 (1984).

[3]International Conference on Highly Charged Ions, Oxford, England, 1984 and Groeningen, The Netherlands, 1986 (unpublished); and International Seminar on Ion-Atom Collisions, Stanford, CA, 1985 and Frankfurt, Federal Republic of Germany, 1987 (unpublished).

[4]H. Beyer *et al.*, J. Phys. B **15**, 3853 (1982); R. Holmes *et al.*, Bull. Am. Phys. Soc. **27**, 513 (1982).

[5]J. Ullrich *et al.*, Nucl. Instrum. Methods (to be published).

[6]R. E. Olson, J. Phys. B **12**, 1843 (1979); A. S. Schlachter *et al.*, Phys. Rev. A **26**, 1373 (1982).

[7]R. T. Short *et al.*, Phys. Rev. Lett. **56**, 2614 (1986).

[8]W. C. Wiley and L. H. McLaren, Rev. Sci. Instrum. **26**, 1150 (1955).

[9]A. Müller *et al.*, Phys. Rev. A **33**, 3010 (1986).

[10]H. Goldstein, *Classical Mechanics,* 2d ed., (Addison-Wesley, New York, 1980).

[11]J. Ziegler *et al.*, *The Stopping and Range of Ions in Solids* (Pergamon, New York, 1985).