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PRODUCTION OF VERY COLD, HIGHLY CHARGED IONS BY SYNCHROTRON RADIATION: COMPARISONS OF THE "SCALPEL" AND "HAMMER" METHODS*

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Measurements of kinetic energies of highly charged argon ions produced by inner-shell photoionization and by ion-beam impact have been made using time-of-flight techniques. High-charge-state recoil ions produced by beams of - .5 - 1 MeV/u Cl^{+5} are found to have energies one to two orders of magnitude higher than ions of the same charge produced by vacancy cascades following inner-shell photoionization by synchrotron radiation. The results may have application to the development of a very-cold ion source useful for angle-resolved atomic collision studies.

Recently we have engaged in an initial study [1] concerning the production of very-low-energy highly charged ions by synchrotron radiation. Our purpose was to measure ion production rates and to verify the cold recoil ion temperatures anticipated, with the possibility in mind of utilizing the method as a lower emittance source of recoil ions than is available using charged-particle impact as the direct ionizing agent (the so-called "hammer" method [2]).

In this study, white and monochromatic x rays from a Stanford Synchrotron Radiation Laboratory wiggler line were used to create single vacancies primarily in the K shells of Ne and Ar, and L shells of Kr and Xe. The subsequent vacancy cascades produced highly charged ions whose recoil energies were found to be so small that they lie well within the range of characteristic energies of the Maxwell-Boltzmann distribution of the room temperature target gas. The ion temperatures observed are $\geq$ 6 orders of magnitude lower than those characteristic of laboratory and stellar plasmas in which ions of corresponding ionization states have comparable abundances. These temperatures are also ~ 2 orders of magnitude smaller than those characteristic of recoil ions produced using the "hammer" method.

Our "scalpel" technique involves use of a time-of-flight (TOF) analyzer to permit joint examination of ion photoproduction rates and energies through study of the yields and widths of the corresponding TOF peaks. These peaks arise from the arrival of ions at a dual channelplate detector $\lesssim$ 1 μs subsequent to their creation by a synchrotron x-ray burst in a dilute gas sample (~0.2 mT) maintained in the extraction region at the front end of the analyzer.

X rays from an 8-pole wiggler operated at 15 kG were focussed by a toroidal mirror and collimated to a 1-mm diameter x-ray beam at the position of the gas target. The critical energy of the radiation was 4 keV (corresponding to the 2-GeV electron-beam energy) and was attenuated below 3 keV by Be windows. This target was viewed by the vertically mounted TOF analyzer through a 3-mm long slit located just above the x-ray beam. X-ray intensity was monitored by ion chambers positioned both up- and downstream of the uhv system housing the analyzer. Typical flux through the target was ~ 10^{12} photons mm^{-2} sec^{-1}, and total ion counting rates in the TOF detector were ~ 1-5 kHz. Detector backgrounds from stray x rays were found to be negligible ($\lesssim$ 3 Hz). The x-ray intensity was sufficient to permit the use of a Si(111) double-crystal monochromator (bandpass 1 x 10^{-4}) to tune radiation above, below, and interleaving the L_1, L_2, L_3 edges of Xe to explore effects of tuning the x-rays through an absorption edge. The timing resolution achieved sufficed not only to make the desired temperature measurements but also to achieve **adjacent mass isotopic resolution** of the charge state (q) spectra of Ne, Ar, Kr, and Xe, as in seen in Fig. 1. Measurements of mean charge state $\bar{q}$ are presented in Table I. The mean charges listed can be compared with pioneering mass-spectroscopic measurements carried out long ago using x-ray guns and filters by Carlson et al. [4], and (for the case of Xe) very recent measurements by Tonuma et al. [5] using monochromatic x-rays from the Photon Factory. In general, the agreement between our results and the measurements of Tonuma et al. is seen to be excellent, resolving a discrepancy we observed [1] in the mean charge state increment measured for Xe as the L_1 edge is crossed. Consideration of Coster-Kronig yields [6] for transfer of an L_1 vacancy to the $L_{2,3}$ subshells and of relative photoionization cross sections of the $L_{1,2,3}$ levels [7] leads to an estimated shift in mean charge state on the order of that seen by our group [1] and by Tonuma et al. [5].

Recently we have applied similar TOF techniques to measure the energies of recoil ions produced using the "hammer" technique (production in a dilute gas sample by fast beams of highly charged heavy ions). Beams of ~ .5 - 1 Mev/u Cl^{+5} produced by the ORNL EN Tandem have been used to create argon and neon recoil ions which have been observed both in "singles" mode (averaged over all scattered ion charge states), and in coincidence with individual scattered ion charge states ranging from 6 to 8 [8].

Mean recoil energies were determined through study of the widths of the corresponding TOF peaks, using procedures similar to those described earlier [1]. For each charge state r the mean initial energy U_0 was deduced from a fit of the peak widths at FWHM to the form

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

The constants α, β, γ represent contributions to measured flight time from, respectively, timing uncertainty; flight time variations due to field fringing; and recoil-ion energy [1,9]. The electric-field scaling parameter (κ) represents six different choices of proportionately scaled [1,9] electric field values in the TOF analyzer. The essential correctness of the Ansatz for Δt^2 was well verified by the clustering of TOF data around fitted quadratic curves, as illustrated in Figure 2 for Ar^{+8} produced by Cl^{+5} at four energies. Recoil energies determined in this manner are summarized in Table II.

The nearly symmetric ion-atom collisions reported here correspond to impact parameters ~ .5 au. [8]. Recoil energies for similar impact parameters estimated by elastic Coulomb scattering theory, in which $E_r \propto (qr)^2$, where q and r are the projectile and recoil charge states, respectively, are an order of magnitude smaller than those we observe. Classical trajectory Monte Carlo (CTMC) calculations [10] of inelastic multiple ionization cross sections for 1 MeV/u collisions of bare ions ($q = 2$-$20,44$) with the rare gases lead to an expression for recoil energy which also scales as $(qr)^2$. When present measurements of log recoil energy are plotted vs log qr ($q = 5$, $r = 6,7,8,9$), the linear dependence observed, Figure 3, suggests a power law of the form $E_r \propto (qr)^n$ where least-squares fit results give $n \sim 10$. This extraordinarily steep dependence is due, in part, to the low q ($q = 5$) used in the fits. Since projectile loss cross sections are large compared to capture cross sections for Cl^{+5} at these energies, most argon recoils are accompanied by scattered projectiles of charge state higher than five. Similar plots for the data obtained in coincidence with scattered projectile charge state suggest an exponent $n \sim 5$. This strong dependence, far steeper than the $n = 2$ obtained for elastic Coulomb scattering and in the CTMC [10] calculations is due primarily to the fact that effective charges seen by the target and projectile nuclei at the moment of closest approach are of much greater importance in determining recoil energy than the asymptotic values (q,r). In fact, good agreement with present measurements is obtained by evaluating the CTMC expression for recoil energy [10] using effective target and projectile charges obtained by Hartree-Fock calculations [8].

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Table II. Comparison of argon recoil ion energies (in eV) produced using unmonochromatized x rays from SSRL with those produced using 18, 23, 27.5, and 33 MeV Cl^{+5} beams from the ORNL EN tandem accelerator.

Argon	SSRL	Cl^{+5} beam (MeV)				
charge	x-rays	18	23	27.6[a]	27.6[b]	33
2	0.046(20) eV					
3	0.050(23)					
4	0.066(21)					
5	0.069(35)	<.2	<.2	<.2	<.2	<.2
6	0.086(36)	.43(.19)	.26(.17)	.09(.29)	.34(.24)	.15(.15)
7	0.092(71)	1.16(.40)	.81(.67)	.62(.61)	.75(.49)	.38(.31)
8	0.081(56)	4.14(.69)	2.69(1.1)	1.84(1.0)	2.28(.84)	1.50(.92)
9		13.91(1.6)	8.21(2.6)	7.17(2.2)	6.82(1.9)	5.03(1.1)

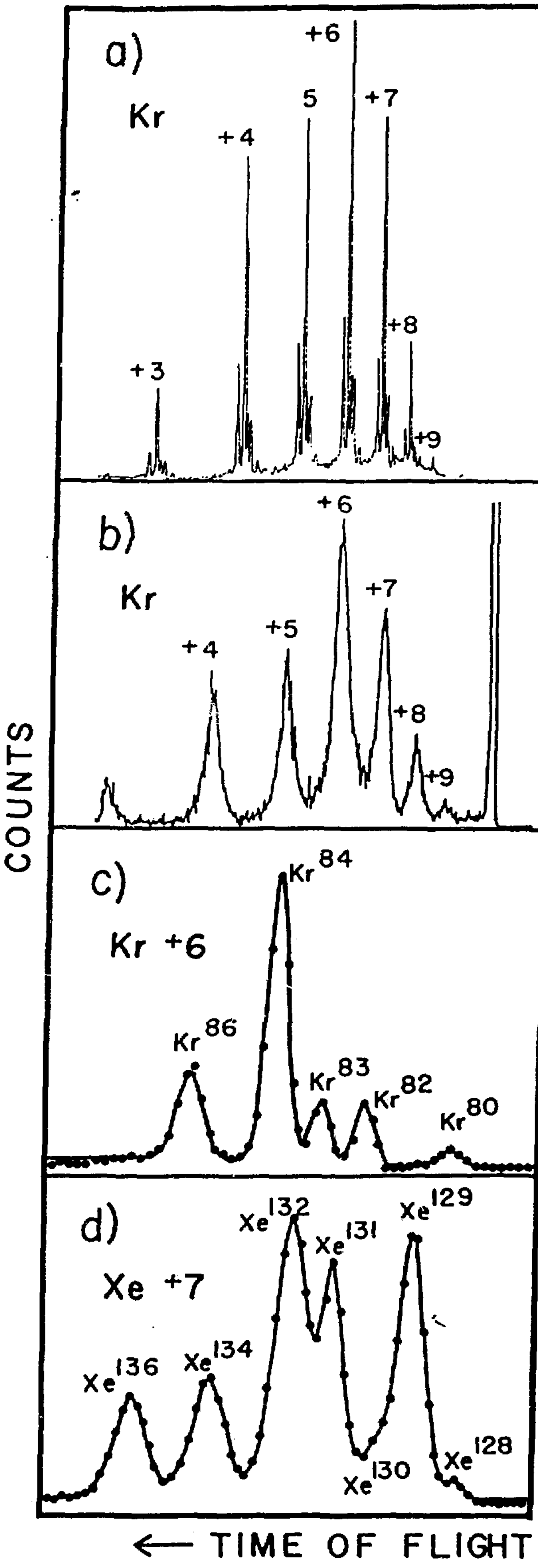
[a] September, 1986. [b] October, 1986.

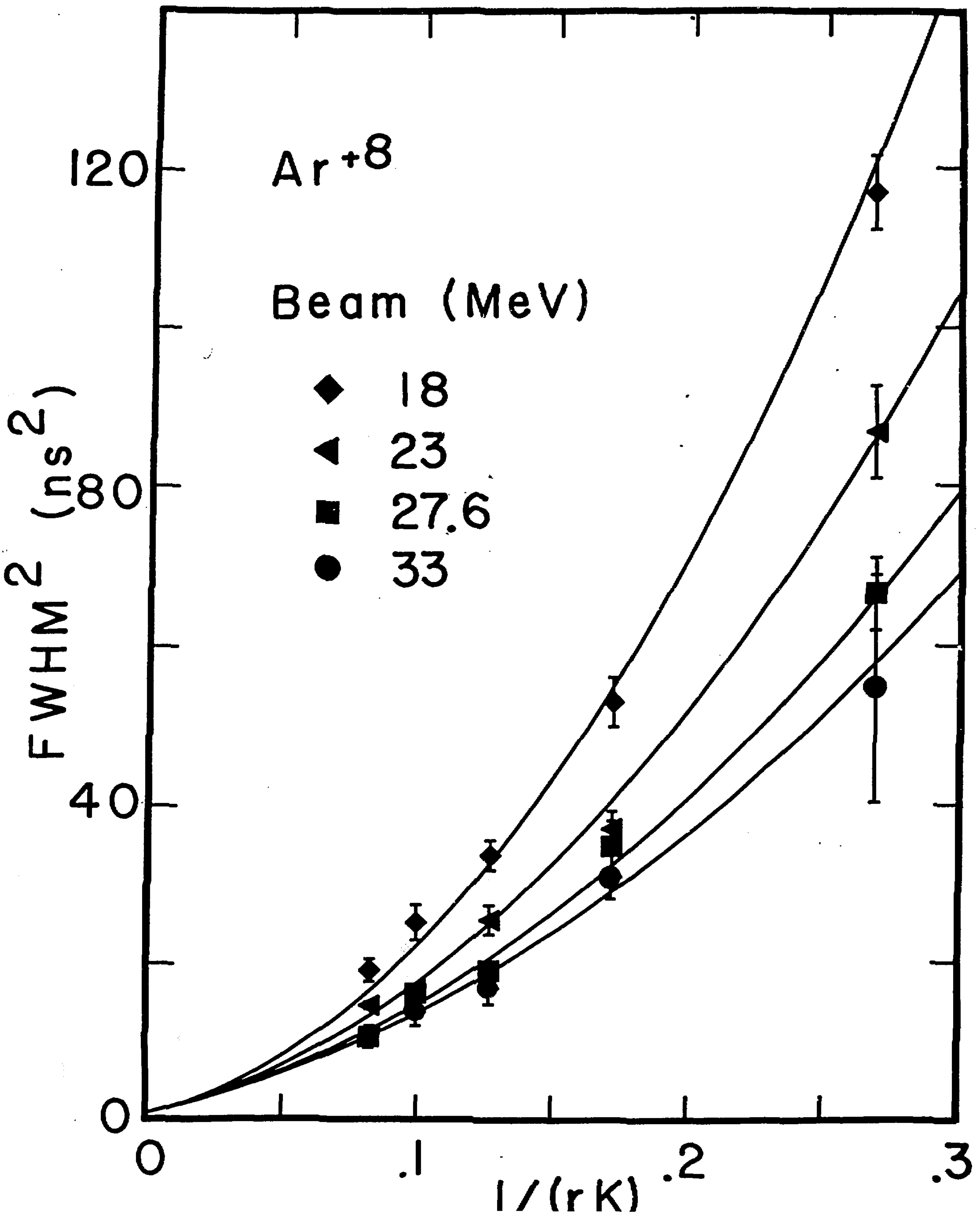
Figure Captions

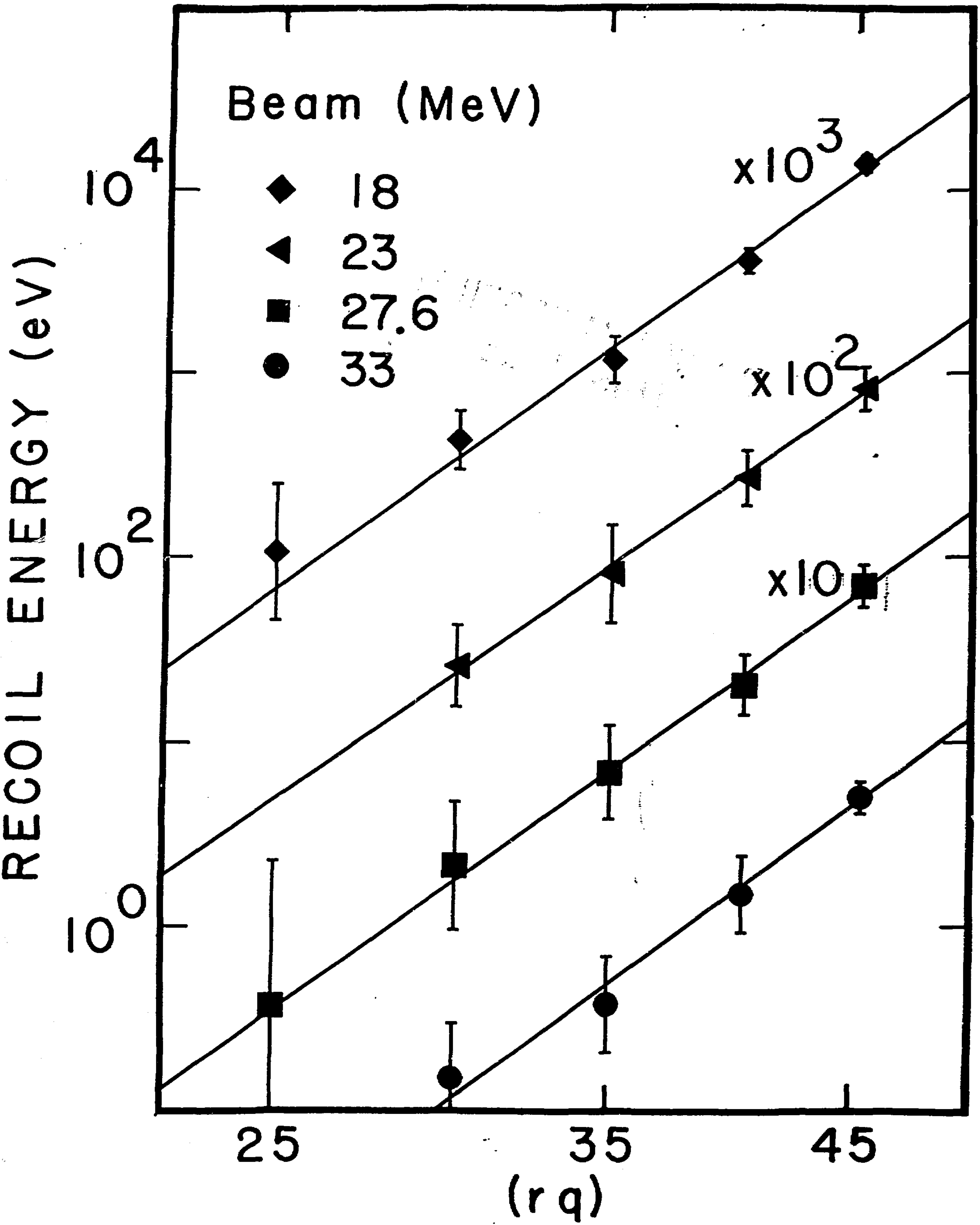
Fig. 1. (a) Kr charge-state distribution following L-shell vacancy production. Plotted is number of ions detected as a function of flight time [1]. (b) Earlier work by Hastings and Kostroun [3] displaying similar results. (c) Expanded view of a Kr peak from (a) demonstrating isotopic resolution [1]. (d) Expanded view of a Xe peak from a typical Xe spectrum [1].

Fig. 2. Quadratic behavior of the square of Ar^{+8} TOF peak widths plotted as a function of $(r\kappa)^{-1}$ (see text) for Cl^{+5} at four beam energies.

Fig. 3. Recoil energy vs product (qr) of incoming projectile charge and recoil charge for beams of 18, 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. The 27.6 MeV data plotted are the average of the data in Table II.


a)
Kr
+3
+4
5
+6
+7
+8
+9
b)
Kr
+4
+5
+6
+7
+8
+9
COUNTS
c)
Kr +6
Kr^86
Kr^84
Kr^83
Kr^82
Kr^80
d)
Xe +7
Xe^136
Xe^134
Xe^132
Xe^131
Xe^130
Xe^129
Xe^128
← TIME OF FLIGHT


Ar^{+8}
Beam (MeV)
◆ 18
◀ 23
■ 27.6
● 33
FWHM^2 (ns^2)
120
80
40
0
0
.1
.2
.3
1/(rK)



RECOIL ENERGY (eV)
(rq)
Beam (MeV)
◆ 18
◀ 23
■ 27.6
● 33
x10³
x10²
x10
10^4
10^2
10^0
25
35
45