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Recoil Ions from Near-Zero-Impact-Parameter H^+-Xe Collisions in the Range 20- 70 keV

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Recoil ions from very small impact-parameter collisions of 20–70-keV protons with xenon atoms were selected by viewing only those ejected at 50° and 70° from the beam direction. These ions were charge-state analyzed and the cross sections determined for the production of charge states up to 6+. In such collisions, multiple ionization accounts for 60–80 % of the ionizing collisions and 80–90 % of the total ionization.

INTRODUCTION

In two previous papers,[1,2] charge-state spectra of recoil ions from very small impact-parameter collisions of protons with rare gases were presented along with some for molecular targets. In collisions with large impact parameters, the target atoms recoil in directions nearly perpendicular to the beam direction. For this study, close collisions were selected by detecting only those recoil ions at large angles from the perpendicular to the beam direction. Angles of 50° and 70° from the beam were used. The rare-gas data showed that not only were close collisions more effective in producing multiply charged ions than more distant collisions, but also that the number of ions produced in high charge states increased with increasing Z of the target. We have now extended this study to include xenon as a target to give a more complete picture.

EXPERIMENTAL RESULTS

The same apparatus was used as for the previous reports.[1,2] An electrostatic analyzer was used to separate the charge states. Cross sections were measured at three target gas pressures from 0.2 to 0.6 mTorr and the final cross sections were obtained by extrapolation to zero pressure. The angular resolution of the detection system was 0.90°, the proton beam angular spread was 0.20°, and the resolution in energy per unit charge of the electrostatic analyzer was 5.5%. The combinations of beam energies (20, 50, and 70 keV) and observation angles used resulted in distances of closest approach small enough that the protons penetrated the N, M, and L shells of xenon and in one case the K shell as well.

Figure 1 shows the recoil-ion spectrum at 50°; the one at 70° is similar. The peaks of a given charge state lie at nearly the same places for different primary energies when plotted versus recoil energy per unit charge divided by the proton energy. Table I gives the cross sections determined from the areas under the peaks. The sum of the cross sections for the various charge states is compared to classical calculations of the total-collision cross sections made using a screened Coulomb potential. The ratio of the experimental to theoretical cross sections gives the ionization efficiency I. The impact parameters p and distances of closest approach r_0 were also calculated assuming a screened Coulomb potential. The measured recoil energies per unit charge E_r/q are also listed and may be compared with the values expected assuming elastic collisions. The approach to agreement is indicated by the ratio of the measured to calculated values, which was 1.04 ± 0.02. The small discrepancy may be due to the assumption of elasticity or to a few percent error in the calibration of the analyzer and/or beam energy.

Figure 2 shows the ratio of cross sections for each charge state to the sum over the charge states for xenon compared to earlier results for krypton and argon. Results for the two angles were averaged, since they were not much different.

Table II gives the fraction of the total-ionization cross section contributed by each charge state for xenon. These are given by the ratio $n\sigma(n)/\sum_n n\sigma(n)$. In Fig. 3 these fractions are plotted, again with the results from the two angles averaged. A comparison is made with the

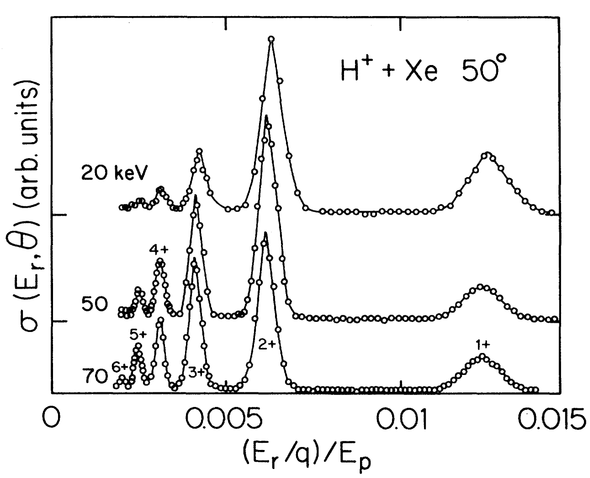

FIG. 1. Recoil-ion spectra at 50° for 20-, 50-, and 70-keV H^+ collisions with xenon. The recoil energy E_r per unit charge has been divided by the proton energy E_p on the horizontal axis to bring the spectra at different energies into line.

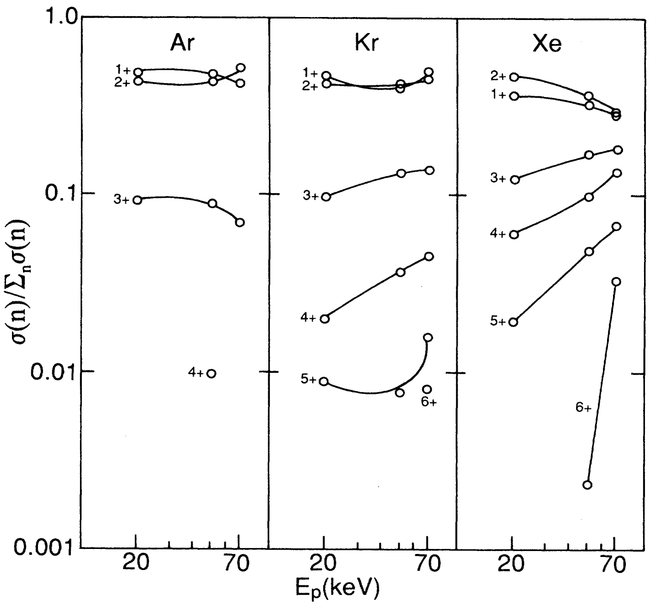

FIG. 2. Fractional cross section for each charge state vs energy. Data from Itoh and Rudd (Ref. 1) for argon and krypton are included for comparison.

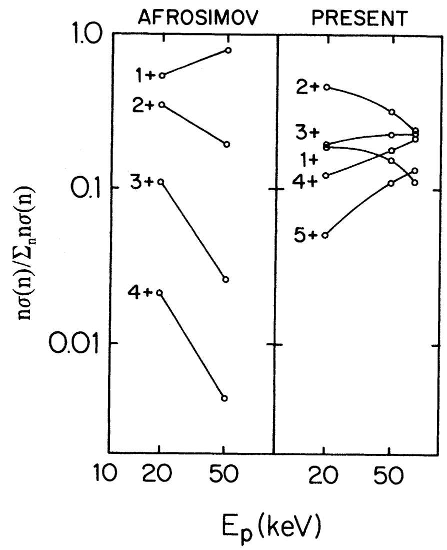

FIG. 3. Fraction of the total ionization due to each charge state vs energy for close $H^+ + Xe$ collisions. Data of Afrosimov *et al.* (Ref. 3) for recoil ions of all impact parameters are shown for comparison.

TABLE I. Cross sections for xenon recoil ions (10^{-25} m^2/sr) and related quantities.

	50°			70°		
	20 keV	50 keV	70 keV	20 keV	50 keV	70 keV
1+	12	2.6	1.5	59	24	13
2+	22	5.3	2.1	87	17	11
3+	7.9	2.9	1.6	18	6.4	5.5
4+	4.3	1.5	1.1	7.4	4.3	4.1
5+	1.2	0.76	0.60	3.0	2.1	1.9
6+			0.25		0.13	1.2
Sum	47	13.1	7.2	174	54	37
Theor.	103	20	11.2	590	132	70
I	0.46	0.66	0.64	0.29	0.41	0.53
$\bar{n}$	2.19	2.42	2.69	1.90	1.96	2.29
p (Å)	0.02	0.0088	0.0065	0.044	0.02	0.0145
r_0 (Å)	0.039	0.018	0.0133	0.058	0.027	0.020
E/q (calc.)	248	621	870	70	176	246
E/q (expt.)	267	635	890	73	180	258

TABLE II. Fractional contributions of various charge states to the ionization of xenon by small-impact-parameter proton collisions.

	50°			70°		
	20 keV	50 keV	70 keV	20 keV	50 keV	70 keV
1+	0.19	0.082	0.077	0.18	0.23	0.15
2+	0.38	0.33	0.22	0.52	0.32	0.26
3+	0.22	0.27	0.25	0.16	0.18	0.20
4+	0.16	0.19	0.23	0.089	0.16	0.19
5+	0.055	0.12	0.15	0.045	0.10	0.11
6+			0.077		0.007	0.085
f[a]	0.81	0.92	0.92	0.82	0.77	0.85

[a] $f = \sum(2\text{–}6)/\sum(1\text{–}6)$.

data of Afrosimov *et al.*,[3] in which recoil ions from all impact parameters were measured. Their data, which are dominated by the much larger number of distant collisions, indicate a smaller fraction of ionization due to multiple ionization than our data, which selected only close collisions. The fraction of the total ionization due to multiple ionization is typically 80–90 %, as indicated in the last line of the table.

Combining the present xenon data with similar data on neon, argon, and krypton from the earlier publications[1,2] shows how the average charge state $\bar{n}=\sum_n n\sigma(n)/\sum_n \sigma(n)$ of the recoil ions increases with the nuclear charge Z. For comparison, the average charge state is taken for collisions for which $r_0 \le r_K$, where r_K is the average radius of the K shell[4] of the target. This quantity has values of 1.1, 1.6, 1.7, and 2.7 for neon, argon, krypton, and xenon, respectively.

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