Electron-transfer and dissociation cross sections of 1.25- to 25-keV H^+, H^0, H^-, and $H_2{}^+$ in collisions with Xe†

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(Received 26 February 1976)

Total collision cross-section measurements of 1.25- to 25-keV H^+, H^0, H^- and $H_2{}^+$ in Xe are reported for the nine processes $H^+ \leftrightarrows H^0$, $H^+ \leftrightarrows H^-$, $H^0 \leftrightarrows H^-$, and $H_2{}^+ \rightarrow [H^+, H^-, (H_2{}^0$ and $H^0)]$. Single- and double-electron-stripping cross sections for which the Xe atom does not change charge are deduced by combining present and past results. Comparisons are made with available experimental data and with theoretical values.

I. INTRODUCTION

In this paper we report measurements of total cross sections of 1.25- to 25-keV H^+, H^0, H^-, and H_2^+ colliding with xenon.[1] Over the present energy range, we are aware of several previous experimental studies of total-cross-section measurements in xenon gas[2–7]; however, there exist gaps in the energy range and some discrepancies in magnitude and in energy dependence of the cross sections. Therefore, we felt it desirable to obtain a self-consistent set of cross sections by measuring the elementary interactions of H^+, H^0, H^-, and H_2^+ with xenon, using the same experimental technique and apparatus for all.

We have made measurements of the following processes in xenon gas:

σ_{10}: $H^+ \rightarrow H^0$ (single-electron capture) ,

σ_{1-1}: $H^+ \rightarrow H^-$ (double-electron capture) ,

σ_{01}: $H^0 \rightarrow H^+$ (single-electron loss) ,

σ_{0-1}: $H^0 \rightarrow H^-$ (single-electron capture) ,

σ_{-10}: $H^- \rightarrow H^0$ (single-electron loss) ,

σ_{-11}: $H^- \rightarrow H^+$ (double-electron loss) ,

σ_+: $H_2^+ \rightarrow H^+$ (proton production) ,

σ_-: $H_2^+ \rightarrow H^-$ (negative-ion production) ,

σ_0: $H_2^+ \rightarrow H_2^0$ and H^0 (neutral production) .

Recently Afrosimov *et al.*[8] have investigated, by a coincidence technique, charge-state changes occurring in the interaction of 5- to 50-keV H^+, H^0, and H^- with xenon gas. With the coincidence method the charge states of the two colliding particles are measured simultaneously but no information is obtained about collisions in which the fast particle changes charge while the target atom does not. However, by combining our measurements with the results of Ref. 8, it is possible to deduce cross sections for collisions of this type. Consequently, we also report cross sections for the following processes over the energy range 5–25 keV:

σ_{-1000}: $H^- + Xe \rightarrow H^0 + Xe + e$
(single-electron stripping) ,

σ_{-1010}: $H^- + Xe \rightarrow H^+ + Xe + 2e$
(double-electron stripping) ,

σ_{0010}: $H^0 + Xe \rightarrow H^+ + Xe + e$
(single-electron stripping) .

There have been a number of previous experimental investigations on xenon targets other than total-cross-section measurements. Those pertinent to the present paper[8–13] as well as total-cross-section measurements outside of and overlapping the present energy range[2–7,14,15] are summarized in Table I.

Several relevant theoretical investigations have been reported in the literature for single-electron capture by protons in Xe at high impact energies; the classical binary-encounter approximation of Gryzinski[16] has been used by Garcia, Gerjuoy, and Welker.[17] They have also modified the Gryzinski formalism in order to avoid divergence in cross-section calculations and to make the method compatible with detailed balancing. Agreement with experimental data for Gryzinski and modified-Gryzinski calculations is poor below 20 keV. (See Sec. III, Fig. 4.) For electron capture at low energies, Shakeshaft and Macek[18] have formulated the coupled-state impact-parameter method for general atom-atom collisions taking full account of electron spin and have applied the method to calculate the single-electron-capture cross section at 0.015, 0.3, and 1.0 keV for proton collisions with xenon. The results of this calculation

TABLE I. Summary of reported measurements for fast hydrogenic projectiles in collision with xenon.

Authors		References	Energy range (keV)	Projectile
Stedeford and Hasted	(1955)	2	0.1–40	H^+, $H_2{}^+$
Fogel *et al.*	(1958–60)	3	2–50	H^+, H^0
Afrosimov *et al.*	(1960)	4	10–100	H^+
Williams and Dunbar	(1966–67)	5	2–50	H^+, H^0, H^-, $H_2{}^+$
Koopman	(1967)	14	0.07–1.05	H^+, $H_2{}^+$
Rozett and Koski	(1968)	9	0.004–0.050	HD^+
Afrosimov *et al.*	(1969)	8	5–50	H^+, H^-, H^0
McNeal *et al.*	(1970)	10	1–25	H^0
LeDoucen *et al.*	(1970)	6	15–150	H^+
Maier II	(1972)	15	0.0005–0.1	H^+
Abignoli *et al.*	(1972)	11	0.5–3	H^+
Dehmel *et al.*	(1973)	12	0.08–2	H^0
Fournier *et al.*	(1974)	13	1–5	H^+, H^0
Brouillard *et al.*	(1975)	7	6	$H_2{}^+$

are in excellent agreement with the experimental results of Koopman[14] (see Sec. III, Fig. 4). The impact-parameter formalism[19] is valid for energies considered in the present work, but we know of no evaluation in this energy range.

We note that at energies below 0.1 keV, well below the energy range covered by the present paper, Maier[15] has applied the approximate theory of asymmetric charge transfer of Rapp and Francis,[20] which has been modified slightly by Lee and Hasted,[21] to the proton-xenon electron-capture reaction. The results of Maier's semiempirical calculation show good agreement with his experimental results for the energy dependence of the cross section.

Lopantseva and Firsov[22] have used perturbation theory to calculate the cross section for single-electron detachment in H^- collisions with rare-gas atoms. They conclude that the cross section σ_{-10} is equal to the cross section for the elastic scattering of free electrons moving at the same velocity as the H^- ion.

We also note that Olson[23] has used curve-crossing arguments to estimate the electron-capture cross sections σ_{0-1} for H(1*s*) and H(2*s*) in Xe. These estimates are stated to be accurate within a factor of 2 at energies below 1 keV.

II. APPARATUS AND PROCEDURE

Ions produced in a low-voltage-arc source[24] were extracted, electrostatically focused, and accelerated. The ions passed between two sets of electrostatic deflection plates which were used to steer the beam both vertically and horizontally. The beam was chopped at a frequency of 3.2 Hz by square-wave modulation of the voltage on one set of steering plates. The beam was then momentum analyzed by a 20° bending magnet and entered the experimental chamber.

Either positive- or negative-ion beams could be directly extracted from the source. During negative-ion operation a magnetic field was provided at the base of the source to suppress electrons. At most energies, the H^- intensity, measured in the experimental chamber, was comparable to or slightly greater than the H^+ intensity. Typical H^+ currents ranged from 1×10^{-8} to 1×10^{-6} A. The $H_2{}^+$ beam intensity was generally an order of magnitude greater than the H^+ beam intensity. The pressure in the accelerator during source operation ranged between 7×10^{-4} and 1.6×10^{-3} Pa (5.3×10^{-6} to 1.2×10^{-5} Torr).

With our accelerator and beam-transport system, low-energy deuterium-ion currents are larger than currents of hydrogen ions of the same velocity. Therefore, low-energy measurements were made with deuterium beams, on the usual assumption that cross sections for all hydrogen isotopes will be the same at a given velocity. At intermediate energies we have demonstrated that this assumption is verified within our experimental uncertainties. However, small systematic differences cannot be excluded.

There always are small $H_2{}^+$ contaminations in D^+ beams, and vice versa. It is possible to estimate this type of contaminant level in a beam by admitting Xe to the target cell and measuring the negative-ion components: The "full-energy" negative-ion signal can only come from D^-, the "half-energy" from H^-; the corresponding D^+ and $H_2{}^+$ populations can then be determined from the cross sections for negative-ion production. In our experiment the $H_2{}^+$ contamination of D^+ beams (and vice versa) was of the order of 0.1%. The effects of this impurity level on our cross-section results are negligible.

A schematic diagram of the experimental arrangement is shown in Fig. 1. The modulated, momentum-analyzed H^+-, H^--, or H_2^+-ion beam of the required energy (within the range 1.25–25 keV) entered a large vacuum chamber, maintained at a pressure of about 1×10^{-4} Pa, through a 1.5-cm-diam aperture and passed through a gas cell which, in the case of H^0 primary beam measurements, served as a neutralizer for the H^+-ion beam. Sufficient hydrogen (or deuterium) gas was admitted to neutralize approximately 50% of the H^+ (or D^+) beam. The residual H^+ ions were electrostatically deflected into a magnetically guarded Faraday cup. When H^+, H_2^+, and H^- beams were desired, the neutralizer cell was evacuated and the ions were not deflected. The primary beam (H^+, H^0, H^-, or H_2^+) then passed through a target cell containing xenon gas. The charged beam components emerging from the target cell were separated electrostatically and collected in magnetically guarded 2.2-cm-diam Faraday cups. The neutral component of the beam was measured with a pyroelectric detector[25] and a phase-sensitive amplifier. The calibration of the detector was checked frequently with charged beams during the taking of data. The H_2^+ Faraday cup was positioned behind the three other detectors (see Fig. 1) so that the dissociation fragments from H_2^+-Xe collisions could be collected as close as possible (25 cm) to the target cell.

The gas-target cell has a 1-mm-diam entrance aperture and a 5-mm-diam exit aperture; these collimators are tubular to reduce the gas flow from the target cell. A simple calculation based

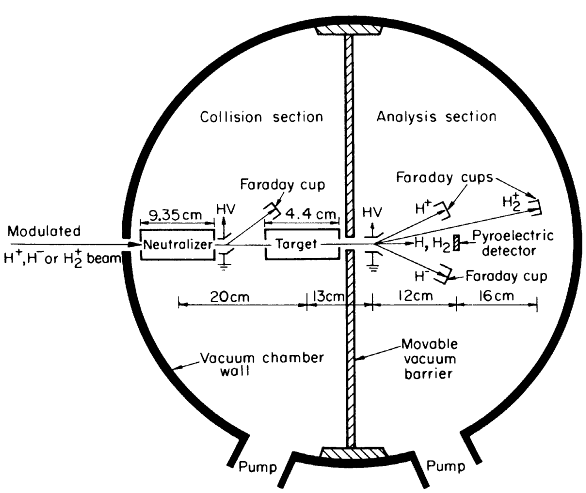

FIG. 1. Diagram of the experimental arrangement.

on conductances and assuming zero pressure at the collimator exits gives an effective cell length of 4.2 cm. The effective length was also calculated with a Monte Carlo code[26]; in this case gas in the beam line outside of the collimators is included. The Monte Carlo result, 4.4 ± 0.1 cm, is used in the data reductions.

A Barocel capacitance manometer was used to determine the xenon gas pressure in the cell. The absolute calibration was checked above 2 Pa with an oil manometer; by interchanging the reference and measurement functions of the two chambers of the capacitance manometer and interpolating the results for both deflections of the manometer diaphragm, we demonstrated linearity for the lower pressures used in the measurements. We estimate a possible standard systematic uncertainty of ±4% in the pressure measurements; combining this with the uncertainty in the gas-cell length and variations in ambient temperature, we estimate ±5% for the target-thickness uncertainty.

All apertures between the target and collectors were large enough so that the Faraday cups and the neutral detector were the limiting apertures. To ensure complete collection of each collision product, the particle detectors were moved from their normal position, both toward and away from the target cell. It was found that the greatest scattering was for D^+ resulting from the dissociation of 2.5-keV D_2^+; therefore, the collection of 1.25-keV D^+ from this reaction was explored in greater detail. For a constant target thickness the D^+ cup was moved such that its acceptance angle ranged from ±50 to ±30 mrad; the D^+ fraction was found to be constant within the experimental uncertainty of ±2% until the acceptance angle was less than ±40 mrad. Since the acceptance angle of the detectors in their normal position is ±44 mrad, the uncertainties due to incomplete particle collection appear to be negligible compared to other uncertainties in the measurements.

The acceleration potential (between source anode and ground) was measured by a high-impedance divider calibrated to ~1% with a high-sensitivity kilovoltmeter. For the low-voltage-arc ion source, we expect the potential drop at the source sheath to be small compared to the lowest acceleration voltage used. The ion-beam energy was taken to be that of the measured acceleration voltage with a standard uncertainty of ±4%.

At each energy, and for each incident ion (H^+, H^0, H^-, or H_2^+), the potential on the electrostatic deflector was adjusted to center the beams on the Faraday cups. For a set pressure in the target gas cell, data were accumulated by recording the signals from the pyroelectric detector and the Faraday cups. Measurements were made at 10–15 different pressures, starting with the background of approximately 5×10^{-4} Pa. The maximum pressure was dictated by the magnitude of the cross sections for competing processes; typically the primary beam was attenuated by less than 15% at the maximum pressure.

All cross sections were obtained from thin-target data. Therefore, to a good approximation[27] each cross section is the slope of the beam-component linear growth curve:

$$\sigma = \frac{dF}{d\pi}, \qquad (1)$$

where F is the observed fractional yield of a given collision product and π is the target thickness (atoms/cm^2). Sample F-vs-π results are presented in Figs. 2 and 3; the lines are the solutions of a least-squares fit to the data (including corrections for second-order terms[27]) from which the cross sections were obtained.

At the lower energies (1.25–3 keV), owing to the loss of sensitivity of the pyroelectric detector (see Ref. 25) and the decrease in primary-beam intensity, the cross sections σ_{10}, σ_{-10}, and σ_0 were determined by measuring the attenuation of the primary beam. In this case the total attenuation cross section can be obtained from

$$\sigma_a = -\frac{dP}{d\pi}, \qquad (2)$$

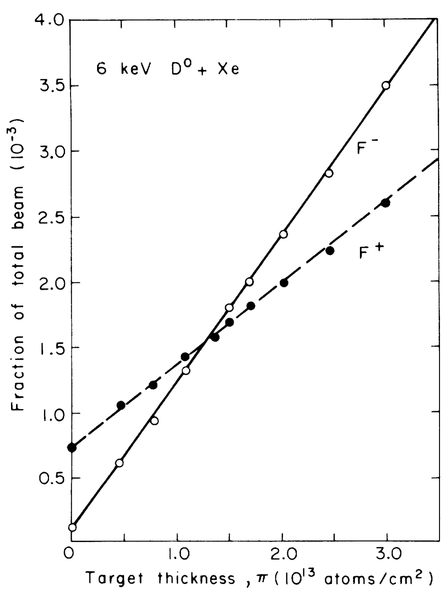

FIG. 2. Measured D^+ and D^- fractions as a function of target thickness for 6-keV D^0 incident on Xe target; the lines are the solutions of a least-squares fit to the data (including corrections for second-order terms, Ref. 27) from which the cross sections were obtained.

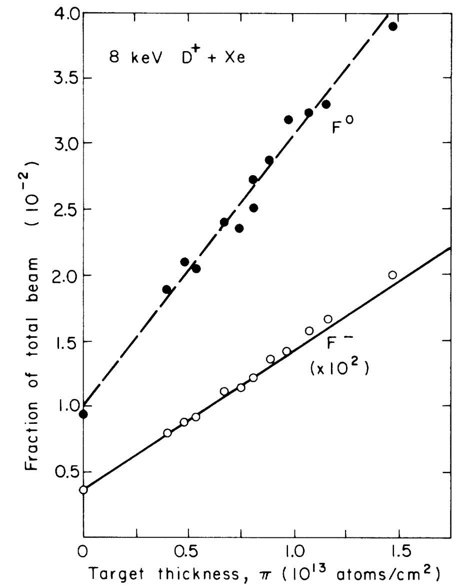

FIG. 3. Measured D^0 and D^- fractions as a function of target thickness for 8-keV D^+ incident on Xe target; the lines are the solutions of a least-squares fit to the data (including corrections for second-order terms, Ref. 27) from which the cross sections were obtained.

where P is the surviving fraction of the primary beam.[27] The cross sections σ_{10}, σ_{-10}, and σ_0 were obtained by subtracting cross sections for the competing loss processes from σ_a, e.g., $\sigma_{10} = \sigma_a - \sigma_{1-1}$. The cross sections for the competing processes were obtained from the growth-curve measurements; in all cases these were less than 5% of σ_a.

From considerations of internal consistency and long-term reproducibility we assign standard relative uncertainties of ±4% to cross sections for charged primary beams and ±7% to cross sections for neutral primary beams, except as noted in the tables. As previously noted, possible systematic experimental uncertainties resulting from pressure measurements and target-thickness calculations are estimated to be within ±5%.

As an independent check of our technique, we measured the single-electron-capture cross section σ_{10} for 10-keV protons in H_2 and compared it with results reported in the literature. The average value of ten independent measurements reported[28] for σ_{10} is $(8.2 \pm 0.3) \times 10^{-16}$ cm^2 per molecule; our result of $(8.1 \pm 0.4) \times 10^{-16}$ is in excellent agreement with this average.

III. RESULTS AND DISCUSSION

A. H^+ collisions

Our experimental single- and double-electron-capture cross sections for energetic protons in xenon are given in Table II; they are also shown in Fig. 4, along with other measurements reported in the literature and the results of theoretical calculations of σ_{10} (see Sec. I). The points obtained by Afrosimov *et al.*[8] with a coincidence technique are the sum of the four cross sections for electron capture when the xenon target is left in charge states +1 through +4. The results of Stedeford and Hasted[2] and those of Koopman[14] were obtained with the condenser-plate method while our cross sections and those of Afrosimov *et al.*,[4] Williams and Dunbar,[5] and LeDoucen *et al.*[6] were derived from growth and attenuation measurements. The discrepancy among the various σ_{10} measurements is slightly greater than the quoted uncertainties (typically 7–10%), but there is no indication of any systematic discrepancy due to different measurement techniques. Our σ_{10} results are in excellent agreement with those of Afrosimov *et al.*[8] and with an extrapolation of cross sections obtained by Shakeshaft and Macek[18] with a three-state impact-parameter calculation (the initial state is the ground state of Xe and the final states are $^2P_{1/2}$ and $^2P_{3/2}$ of Xe^+).

In the case of double-electron capture, our results agree very well with two previous measurements obtained from growth and attenuation measurements[3,5] and the sum of the appropriate partial cross sections of Afrosimov *et al.*[8] for energies greater than 8 keV. Our results confirm the previously reported maximum[3,5] in σ_{1-1} at about 3 keV, although our values for the cross sections are larger.

B. H^0 collisions

Our results for the cross sections for electron loss, σ_{01}, and capture, σ_{0-1}, for collisions between H atoms and xenon are given in Table II. They also are shown in Fig. 5, along with the results of other investigators.[3,5,8] The discrepancy between our measurements and those of Ref. 5 is striking and far outside the estimated uncertainties of the two experiments.

As others have noted (see, e.g., Ref. 5), these cross sections can be affected by the fraction of the incident neutral beam in excited states, either the metastable 2*s* or long-lived highly excited

TABLE II. Electron-capture and -loss cross sections for collisions of D^+, D^0, D^-, H^+, H^0, and H^- with Xe. Relative uncertainties are as shown in column headings except as noted. Not included are systematic uncertainties which are estimated to be less than ±5%.

Incident projectile	Energy (±4%) (keV)	Cross sections (10^{-17} cm^2/atom)					
		σ_{10} (±4%)	σ_{1-1} (±4%)	σ_{01} (±7%)	σ_{0-1} (±7%)	σ_{-10} (±4%)	σ_{-11} (±4%)
D^+, D^0, or D^-	2.5	264	0.34 [a]			118	1.9
	3.0		0.38 [b]			118	2.2
	4.0	272	0.90	6.5	8.5		
	4.4		1.18				
	5.0	236	1.36	6.2	10.6	138	2.9
	5.7	248	1.30				
	6.0			6.2	10.8		
	6.6	231 [c]	1.30				
	6.9			6.3	11.0	156 [a]	3.4
	8.0	205	1.03	6.3	9.4	169	4.0
	10.0	194	1.12	8.4	8.5	176	5.0
	12.5			9.4	7.4	194	6.1
	15.0	166	1.59				
	20.0	154	1.78	14	5.9	215	9.7
H^+, H^0, or H^-	5.4			8.0	8.6		
	9.2			13	6.0		
	12.0			18	6.1		
	12.5	141	2.04			238	11.8
	13.2			18	5.7		
	15.3	124	1.97			235	12.9
	18.0	118	1.92	24	4.9	234	14.6
	20.0			28	4.6		
	22.0		1.71	33	3.5	218	17.1
	25.0		1.50	38	3.0	220	18.7

[a] ±7%.
[b] ±10%.
[c] ±15%.

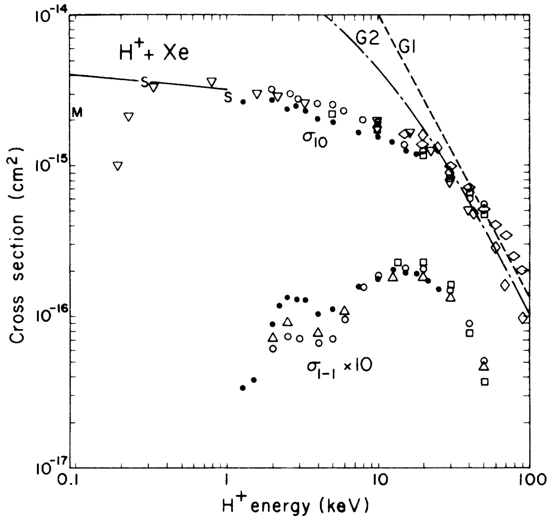

FIG. 4. Cross sections σ_{10} and σ_{1-1} for single- and double-electron capture for collisions of energetic H^+ ions with Xe. σ_{10}: ●, present results; ∇, Stedeford and Hasted (Ref. 2); □, sum of partial cross sections measured by Afrosimov *et al*. (Ref. 8) (see text); ◇, Afrosimov *et al*. (Ref. 4); ○, Williams and Dunbar (Ref. 5); ◇, LeDoucen *et al*. (Ref. 6); ——, Koopman (Ref. 14); curve G1, Gryzinski calculation of Garcia *et al*. (Ref. 17); curve G2, modified Gryzinski calculation of Garcia *et al*. (Ref. 17); S, impact parameter calculation of Shakeshaft and Macek (Ref. 18); M, calculation by Maier (Ref. 15). σ_{1-1}: ●, present results; ○, Williams (Ref. 5); △, Fogel *et al*. (Ref. 3); □, sum of partial cross sections measured by Afrosimov *et al*. (Ref. 8) (see text). Note: the cross sections σ_{1-1} have been multiplied by 10. The cross sections for D^+ have been plotted at one-half the D^+ energy.

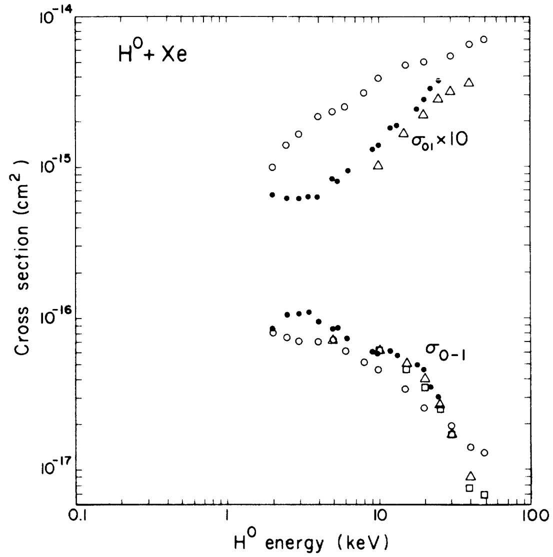

FIG. 5. Cross sections σ_{01} and $\sigma_{0\,-1}$ for electron loss and capture for collisions of energetic H^0 atoms with Xe. σ_{01}: ●, present results; ○, Williams (Ref. 5); △, Fogel *et al*. (Ref. 3). Note: the cross section σ_{01} has been multiplied by 10. $\sigma_{0\,-1}$: ●, present results; ○, Williams (Ref. 5); □, sum of partial cross sections measured by Afrosimov *et al*. (Ref. 8) (see text); △, Fogel *et al*. (Ref. 3). The cross sections for D^0 have been plotted at one-half the D^0 energy.

states. We address this problem in the Appendix, where we show that the H(2*s*) are quenched in the electric field used to sweep the ions out of the beam and that long-lived highly excited H atoms with principal quantum numbers $5 \lesssim n \lesssim 25$ may contribute 0.15% to the H beam at 5 keV and 0.9% at 25 keV. We estimate that these excited-atom "impurities" might, at most, account for 9% of our σ_{01} cross sections.

C. H^- collisions

Our electron-loss cross sections, σ_{-10} and σ_{-11}, are also listed in Table II; they are shown in Fig. 6 along with previous results.[2,5] The results of Williams[5] are a direct measurement of σ_{-10} whereas Stedeford and Hasted,[2] who used the condenser-plate method, measured $\sigma_{-10}+2\sigma_{-11}$. We are not aware of previous measurements of σ_{-11} with which to compare the present data.

The calculated results of Lopantseva and Firsov[22] for σ_{-10} have a maximum value at about 12

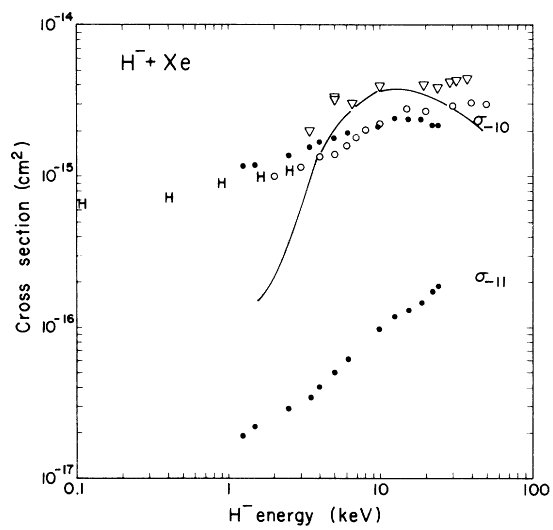

FIG. 6. Cross sections σ_{-10} and σ_{-11} for single- and double-electron loss for collisions of energetic H^- ions with Xe gas. σ_{-10}: ●, present results; ○, Williams (Ref. 5); H, Hasted (Ref. 2); ∇, Stedeford and Hasted ($\sigma_{-10}+2\sigma_{-11}\approx\sigma_{-10}$) (Ref. 2); Solid line, Lopantseva and Firsov (Ref. 22). σ_{-11}: ●, present results. The cross sections for D^- have been plotted at one-half the D^- energy.

keV, in agreement with our results. However, the general agreement is poor, especially at the lower energies.

D. Electron stripping

We can obtain the cross sections for single (σ_{-1000} and σ_{0010}) and double (σ_{-1010}) electron stripping processes in which the Xe atom is not ionized (see Sec. I) by subtracting from our total electron-loss cross sections ($\sigma_{-10}, \sigma_{-11}$, and σ_{01}) the appropriate partial cross sections measured by Afrosimov *et al.*[8] for electron loss with accompanying single and multiple ionization of the target xenon atoms. The results of the subtraction are shown in Fig. 7 as dashed lines. For comparison we have included our total electron-loss cross sections as solid lines in Fig. 7. We see that the stripping collision is the dominant electron-loss mechanism over the present energy range.

We do not know what uncertainties to assign to these cross sections since they are obtained by taking the difference of our results and those of Ref. 8, for which no uncertainty estimates are reported. We note, however, that our electron-capture cross sections are generally in good agreement with the sum of the partial cross sections reported by Afrosimov *et al.*[8] (see Figs. 4 and 5).

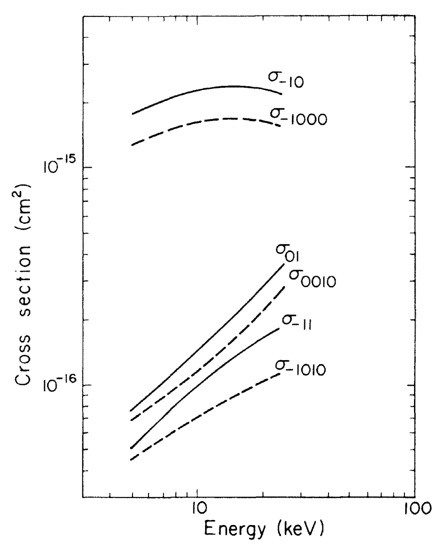

FIG. 7. Comparison of total electron-loss cross sections with electron-stripping cross sections. Solid curves: present results for total electron-loss cross sections σ_{-10}, σ_{01}, and σ_{-11}; dashed curves, derived results for electron-stripping cross sections σ_{-1000}, σ_{0010}, and σ_{-1010} (see text).

E. H_2^+ collisions

We have measured cross sections for H^+ production (σ_+), H^- production (σ_-), and neutral production (σ_0) in H_2^+-Xe collisions. The cross section σ_+ arises from the following processes[29]:

$$\sigma_1:\ H_2^+ \to H^+ + H^0$$
$$\sigma_2:\ \to H^+ + H^+ + e$$
$$\sigma_5:\ \to H^+ + H^- - e\ .$$

Therefore the measured cross section is $\sigma_+ = \sigma_1 + 2\sigma_2 + \sigma_5$.

The cross section σ_- arises from the processes

$$\sigma_5:\ H_2^+ \to H^+ + H^- - e$$
$$\sigma_6:\ \to H^0 + H^- - 2e$$
$$\sigma_7:\ \to H^- + H^- - 3e\ .$$

The measured cross section is $\sigma_- = \sigma_5 + \sigma_6 + 2\sigma_7$.

The cross section σ_0 arises from the processes

$$\sigma_1:\ H_2^+ \to H^0 + H^+$$
$$\sigma_3:\ \to H^0 + H^0 - e$$
$$\sigma_4:\ \to H_2^0 - e$$
$$\sigma_6:\ \to H^0 + H^- - 2e\ .$$

Since the pyroelectric detector measures a signal proportional to the power deposited at the detector, the measured cross section is the total neutral-power-production cross section and is given by $\sigma_0 = \frac{1}{2}\sigma_1 + \sigma_3 + \sigma_4 + \frac{1}{2}\sigma_6$. (The cross section σ_4 has recently been measured separately.[30])

Our results for σ_+, σ_-, and σ_0 are given in Table III and shown in Fig. 8 along with other relevant

TABLE III. Cross sections, σ_0, σ_+, and σ_- (see text), for collisions of D_2^+ and H_2^+ with Xe. Relative uncertainties are ±4% except as noted. Not included are systematic uncertainties which are estimated to be less than ±5%.

Incident projectile	Energy (±4%) (keV)	Cross sections (10^{-17} cm^2/atom) σ_0	σ_+	σ_-
D_2^+	2.5	258	9.1	0.079 [a]
	3.0	258 [a]	9.7	0.095 [a]
	4.0	245		
	5.0	230	12.2	0.155
	7.0	227	15.2	0.231
	10.0	224	17.0	0.32 [a]
	15.0	206	18.1	0.34
	20.0	193	19.2	0.35
H_2^+	10.1	188	19.0	0.36
	13.0	182	20.0	0.36
	16.5	172	20.8	0.31
	20	156	22.9	0.27
	25	153 [a]	23.2	0.265

[a] ±7%.

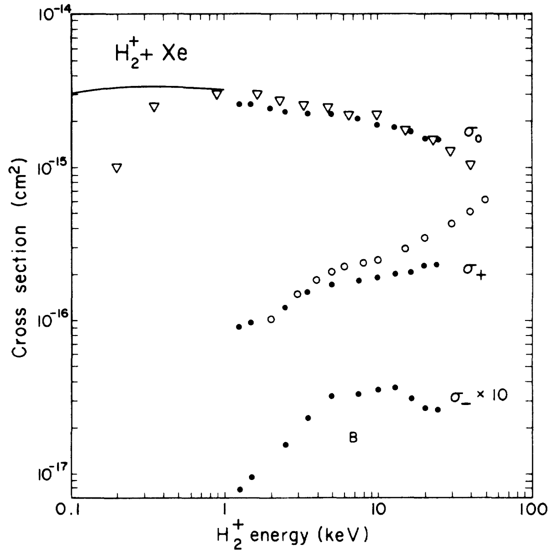

FIG. 8. Cross sections σ_0, σ_+, and σ_- for the formation of H_2 and H, H^+, and H^- for collisions of energetic H_2^+ ions with Xe gas. σ_0: ●, present results. σ_{cx} (see text): ▽, Stedeford and Hasted (Ref. 2); solid line, Koopman (Ref. 14). σ_+: ●, present results; ○, Williams and Dunbar (Ref. 5). σ_-: ●, present results; B, Brouillard *et al.* (Ref. 7). Note: the cross section σ_- has been multiplied by 10. The cross sections for D_2^+ have been plotted at one-half the D_2^+ energy.

measurements.[2,5,7,14] The cross section σ_- has a maximum centered around 10 keV. A measurement at 6 keV by Brouillard *et al.*[7] is also shown. The only other measurements of which we are aware are unpublished results of Williams[31]; these are not shown because of the large scatter in the measurements.

We are not aware of any direct measurements of σ_0; there are, however, measurements of "charge-exchange" cross sections, σ_{cx}, obtained by collecting slow ions and electrons in the target chamber—the condenser-plate method used by Stedeford and Hasted[2] and by Koopman.[14] It can be shown that $\sigma_{cx} = \sigma_0 - (\frac{1}{2}\sigma_1 + \sigma_2 - \sigma_5 - \frac{3}{2}\sigma_6 - 3\sigma_7)$. Although none of the cross sections in the parentheses are known individually,[32] these cross sections can be expressed in terms of σ_+ and σ_-: $\sigma_0 - \sigma_{cx} = \frac{1}{2}(\sigma_+ - 3\sigma_-)$. When the right-hand side of this equation is evaluated with the cross sections listed in Table III, we see that at our highest energy σ_0 exceeds σ_{cx} by only 8%, and by less than 2% at our lowest energy. Therefore, within the experimental uncertainties, we can equate σ_0 and σ_{cx}; from Fig. 8 we see that there is good agreement.

It is well known that the interpretation of experimental data for collisions involving fast H_2^+ primary beams is complicated since it is difficult to specify the degree of vibrational excitation of the primary H_2^+ ion. Depending on the ion-source type and its operating conditions, measured values of dissociation cross sections have been found to vary as much as 30%.[5,33] We used a low-voltage-arc source; Stedeford and Hasted,[2] a hot-filament reflecting-arc discharge; Williams and Dunbar[5] and Koopman,[14] a radio-frequency ion source; and Brouillard *et al.*[7] a duoplasmatron. In spite of the variations in ion sources, there is good agreement among the results for σ_0 shown in our energy range; agreement between the σ_+ results is not good at the higher energies.

IV. CONCLUDING REMARKS

Estimates of the absolute uncertainties associated with cross sections shown in Figs. 4–8 cannot be obtained from the literature in all cases. To avoid cluttering the graphs we have not shown any error bars. However, we note that the results of separate experiments often differ by many standard deviations.

ACKNOWLEDGMENTS

One of us (T. J. M.) takes pleasure in thanking Dr. R. V. Pyle for the opportunity to participate in the present investigation. The assistance of D. Leung and P. J. Schneider during the acquisition of data is gratefully appreciated. V. J. Honey provided valuable assistance in maintenance of the electronic equipment. We also thank R. C. Wolgast for his assistance in carrying out the Monte Carlo calculations of the density profile in the target cell.

APPENDIX: ESTIMATE OF THE EXCITED-ATOM POPULATION IN THE H BEAM

With our apparatus we would not directly measure the excited-atom content of the H beam (produced by $H^+ + H_2$ collisions) used for the σ_{01} and σ_{0-1} measurements. In this appendix we estimate the magnitude of the excited-atom "impurity" level and its effect on the cross sections. We show that the H(2*s*) are quenched in the electric field used to sweep the ions out of the beam and that long-lived highly excited H atoms with principal quantum numbers $5 \lesssim n \lesssim 25$ may contribute 0.15% to the H beam at 5 keV and 0.9% at 25 keV. We estimate that these excited-atom "impurities" might, at most, account for 9% of our σ_{01} cross sections. Changes in the method of producing the H beam, which should have altered the excited-atom population by a factor of 2, had no effect on our results for σ_{01} or σ_{0-1}.

The metastable H(2*s*) atoms were quenched by the electric field (1 kV/cm for 2.5-keV D^+ up to

10 kV/cm for 25-keV H^+) that was applied along 2.5 cm of the beam path to deflect the ions: The H(2s) lifetime in these electric fields ranges from 4.2×10^{-9} to 3.3×10^{-9} sec,[34] whereas the time-of-flight through the electric field region ranged between 5×10^{-8} sec for the 2.5-keV D atoms to 1.2×10^{-8} sec for the 25-keV H atoms. Thus the time spent in the electric field was always longer than ~4 times the H(2s) lifetime. Combining this with the relatively small probability of forming H(2s) [$\sigma(H^+ + H_2 \to H(2s)) \approx 0.1\sigma_{10}$ for energies covered in our work[35]], we conclude that the H(2s) contamination in our H beams was at most 0.2% at 25 keV and even less at the lower energies.

For the higher quantum levels n, we assume, for purposes of this discussion, that the angular momentum states l have a statistical $(2l+1)$ population distribution, so that we are concerned only with the principal quantum number n. With this assumption the radiative lifetime of a level n is not affected by the presence of the electric field (i.e., the statistically averaged field-free and Stark lifetimes are identical).[36] For the velocity range covered in our experiment the $n = 5$ level will have decayed to $\sim e^{-1}$ of its initial population in the ~10-cm distance between the neutralizer and target cells; the lower levels, with their shorter lifetimes, will have decayed even more. For a worst-case analysis we consider all quantum levels with $n \leq 4$ to have decayed to an insignificant population and all levels with $n \geq 5$ to arrive at the target cell without radiative decay.

Results of experiments in which highly excited H atoms are field ionized (see, for example, Refs. 37–39) have been consistent with the assumption that the fraction of atoms in quantum level n, $R(n)$, in a beam produced by charge exchange is given by

$$R(n) = \alpha n^{-3} ,$$

where the coefficient α, for a given target gas, is a function of the energy and the target thickness. (Although the field-ionization experiments have been limited to $n \gtrsim 8$, calculations by Hiskes[40] show that the n^{-3} relationship is applicable for levels with $n \gtrsim 5$.)

Of the various field-ionization measurements reported in the literature, those of McFarland and Futch[39] most nearly coincide with the energy range of our experiment; these authors have measured the coefficient α for 5–30-keV H atoms produced by charge transfer in H_2. For the H_2 neutralizer thicknesses used in our experiment ($\sim 6 \times 10^{14}$ cm^{-2}) their values of α are 0.06, 0.15, and 0.4 at 5, 10, and 25 keV.

We must consider one more effect before we can evaluate the excited-atom population. The electric field that quenches the H(2s) also field-ionizes the very high quantum levels above a threshold level n_T. From Ref. 41 we see that the n_T values are approximately 25, 20, and 16 at 5, 10, and 25 keV (for which deflection fields of 2, 4, and 10 kV/cm were applied).

For our experiment, then, an estimate of the fraction of the beam in highly excited states is given by the expression

$$f = \sum_{n=5}^{n_T} \alpha n^{-3} .$$

Using the α values reported by McFarland and Futch,[39] we obtain 0.15, 0.35, and 0.9% at 5, 10, and 25 keV. We note that, since we neglected radiative decay in this calculation, these should be upper limits.

We now consider what effect these impurity levels could have on our results for σ_{01} in Xe. Butler and May[42] have proposed that the cross section for the ionization of a highly excited hydrogen atom is independent of the quantum number n and is equal to the total scattering cross section for a free electron moving at the velocity of the excited H atom. The total electron scattering cross sections in Xe at the velocities of 5-, 10-, and 25-keV H atoms are 2×10^{-15}, 3.5×10^{-15}, and 3×10^{-15} cm^2.[43] (The decrease in the cross section at 5 keV reflects the depression in the electron scattering cross section by the Ramsauer effect. Although it is not clear that the diffraction of a loosely bound electron is the same as that of a free electron, we will make that assumption for our estimates.) When we multiply these cross sections by our estimates of the excited-atom fractions, we find that the contribution of excited-atom "impurities" to our σ_{01} result is, at most, 4, 9, and 7% at 5, 10, and 25 keV.

We know of no calculations or estimates for electron capture by highly excited H atoms [$H(n) + Xe \to H^-$] and thus are unable to estimate the effect of excited states on our σ_{0-1} cross sections. We note, however, that Olson[23] has made estimates for $H(2s) + Xe \to H^-$ below 2 keV and has found that for Xe there is only a small enhancement over electron capture by the ground state.

We performed two separate tests to experimentally confirm that excited H atoms did not appreciably contribute to our measured cross sections. McFarland and Futch[39] observed that at low energies the value of α doubled as the H_2 target thickness was increased from 4×10^{14} to 6×10^{15} cm^{-2} and that the thick-target value of α is approximately 0.12 below 10 keV. For 4-keV D^0 we observed no change (within our random uncertainty of ±7%) in either σ_{01} or σ_{0-1} as the neutralizer thickness was varied from $\sim 6 \times 10^{14}$ to $\sim 6 \times 10^{15}$

(D_2 molecules)/cm^2; this suggests cross-section upper limits of 4×10^{-15} cm^2 for $H(n)+Xe\rightarrow H^+$ (consistent with the electron scattering model) and 5 $\times10^{-15}$ cm^2 for $H(n)+Xe\rightarrow H^-$. In another attempt to alter the highly-excited-atom content of the H beam, we produced the H atoms by electron detachment of H^- in H_2, since at very high energies it has been demonstrated that the highly-excited-atom populations are smaller when the H atoms are formed by electron detachment.[44] [Although electron-detachment may enhance the H(2*s*) population over that resulting from electron capture,[45] we have already shown that the H(2*s*) are quenched in the electric field between the neutralizer and target cells.] No changes in our σ_{01} and σ_{0-1} results were observed when we repeated the measurements at several energies with H beams produced by electron detachment of H^-.

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†Work performed under the auspices of the U.S. Energy Research and Development Administration.

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