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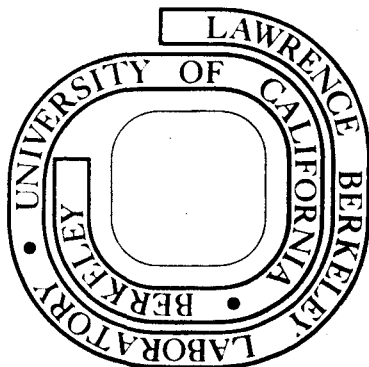
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ELECTRON-TRANSFER AND DISSOCIATION CROSS SECTIONS OF 1.25- TO
25-keV H^+ , H^0 , H^- , and H_2^+ IN COLLISIONS WITH Xe^+

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ABSTRACT

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 $H^+ \rightarrow H^0$, $H^+ \rightarrow H^-$, $H^0 \rightarrow H^-$, and $H_2^+ \rightarrow [H^+, H^-, (H_2^0 \text{ and } H^0)]$. Single and double electron-stripping cross sections for which the Xe atom does not change charge, deduced from combining present and past results, are also reported. Comparisons are made with available experimental data and with theoretical values.

I. INTRODUCTION

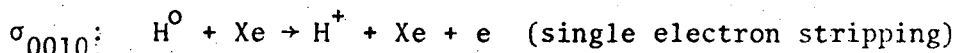
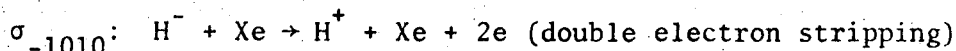
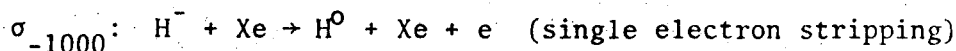
In this paper we report measurements of total cross sections of 1.25- to 25-keV H^+ , H^0 , H^- , and H_2^+ colliding with xenon.¹ Over the present energy range, we are aware of several previous experimental studies of total cross-section measurements in xenon gas;²⁻⁷ however, there exist gaps in the 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 between H^+ , H^0 , H^- , and H_2^+ and xenon with the same experimental technique and apparatus.

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- to 25-keV:



There have been a number of previous experimental investigations on xenon targets other than total cross-section measurements. Those pertinent to the present paper⁸⁻¹³ as well as total cross-section measurements outside of and overlapping the present energy range^{2-7,14,15} are summarized in Table I.

Relevant theoretical investigations are limited to single electron-capture by protons. For high impact energies, the classical binary-encounter approximation of Gryzinski¹⁶ has been used by Garcia, Gerjuoy and Welker.¹⁷ They have also modified the Gryzinski formalism in order to avoid divergent cross sections 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 Section III, Fig. 2.) For electron capture at low energies, Shakeshaft and Macek¹⁸ 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 are in excellent agreement with the experimental results of Koopman¹⁴ (see Section III, Fig. 2). The impact parameter formalism¹⁹ 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, Maier¹⁵ 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 semi-empirical calculation show good agreement with his experimental results for the energy dependence of the cross section.

II. APPARATUS AND PROCEDURE

Ions produced in a low-voltage-arc source²² 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} A 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 stack during source operation ranged between 7×10^{-4} Pa and 1.6×10^{-3} Pa.

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 can not be excluded.

There always are small H_2^+ contaminations in D^+ beams, and vice-versa. The effects of these contaminations have been shown to be insignificant in our experiment.

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 to 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 detector²³ 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 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 code²⁴; 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 $\pm 4\%$ in the pressure measurements; combining this with the uncertainty in the gas-cell

length we estimate $\pm 5\%$ 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 mrad to ± 30 mrad; the D^+ fraction was found to be constant within the experimental uncertainty of $\pm 2\%$ 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 $\sim 1\%$ 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 $\pm 4\%$.

All cross sections were obtained using thin-target data. Therefore, to a good approximation²⁵ each cross section is the slope of the beam-component linear growth curve:

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

where F is the observed fractional yield of a given collision product and π is the target thickness (atoms/cm²).

At the lower energies (1.25- to 3-keV), due to the loss of sensitivity of the pyroelectric detector (see Ref. 23) 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

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

where P is the surviving fraction of the primary beam.²⁵ 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 H₂ and compared it with results reported in the literature. The average value of ten independent measurements reported²⁶ for σ_{10} is $(8.2 \pm 0.3) \times 10^{-16}$ cm² 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. 2, along with other measurements reported in the literature and the results of theoretical calculations of σ_{10} (see Section 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 Hasted² and those of Koopman¹⁴ 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 to 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 Macek¹⁸ 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. H⁰ 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. 3, along with the results of other investigators.^{3,5,8} 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 2s or long-lived highly excited states. We have applied 2s quenching electric fields of 140 to 4000 V/cm without affecting either σ_{01} or σ_{0-1} . Riviere and Sweetman²⁷ have shown that the population of long-lived excited atoms is altered by a change in the target thickness; therefore, to test for the effect of highly-excited atoms we changed the target thickness of the neutralizer cell. No change in the measured values of σ_{01} or σ_{0-1} was observed as the H₂(D₂) neutralizer thickness was varied from 4×10^{14} to 10^{16} molecules/cm². Finally, one would expect very few excited H atoms to be formed by electron-detachment of H⁻. We therefore spot-checked some of our σ_{01} and σ_{0-1} measurements with H beams produced from H⁻ and again observed no effect. From this we conclude that it is unlikely that we had an appreciable contamination of excited atoms in our H beam.

The discrepancy between our measurements and those of Ref. 5 is striking and far outside the estimated uncertainties of the two experiments.

C. H⁻ Collisions

Our electron-loss cross sections, σ_{-10} and σ_{-11} , are also listed in

Table II; they are shown in Fig. 4 along with previous results.^{2,5} The results of Williams⁵ 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.

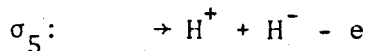
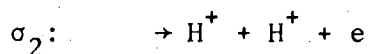
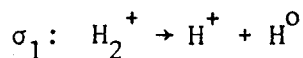
D. Electron Stripping

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 Section I) by subtracting from our total electron-loss cross sections (σ_{-10} , σ_{-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. 5 as dashed lines. For comparison we have included our total electron-loss cross sections as solid lines in Fig. 5. 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 results obtained at two different laboratories. 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. 2 and 3).

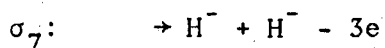
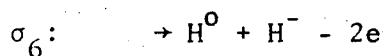
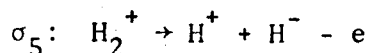
E. H₂⁺ Collisions

We have measured cross sections for H⁺ production (σ_+), H⁻ production (σ_-), and neutral production (σ_0) in H₂⁺-Xe collisions. The cross section σ_+ arises from the following processes²⁸



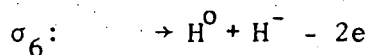
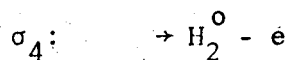
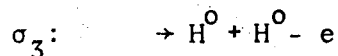
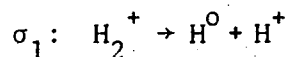
Therefore the measured cross section is $\sigma_+ = \sigma_1 + 2\sigma_2 + \sigma_5$.

The cross section σ_- arises from the processes



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

The cross section σ_0 arises from the processes



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.²⁹⁾

Our results for σ_+ , σ_- , and σ_0 are given in Table III and shown in Fig. 6 along with other relevant 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 by Williams³⁰; 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, "charge exchange" measurements obtained by collecting slow ions and electrons in the target chamber -- the condenser-plate method used by Stedeford and Hasted² and by Koopman.¹⁴ It can be shown that " σ_{cx} " = $\sigma_0 - (\frac{1}{2}\sigma_1 + \sigma_2 - \sigma_5 - 3/2\sigma_6 - 3\sigma_7)$. Although none of the cross sections in the brackets are known individually,³¹ these cross sections can be expressed in terms of σ_+ and σ_- : $\sigma_0 - "$ σ_{cx} " = $\frac{\sigma_+ - 3\sigma_-}{2}$. 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 compare σ_0 and " σ_{cx} "; from Fig. 6 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%.^{5,32} We used a low-voltage arc source; Stedeford and Hasted,² a hot-filament reflecting-arc discharge; Williams and Dunbar⁵ and Koopman,¹⁴ a radio-frequency ion source; and Brouillard et al.⁷ a duo-plasmatron. 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. 2-6 can not 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

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Footnotes and References

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

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24. The Monte-Carlo Code used was developed at the UKAEA Culham Laboratory by J. N. Chubb: UKAEA Culham Laboratory Report CLM-R 54 (1966); Vacuum 16, 591 (1966).
25. The cross sections presented in the tables and figures were actually obtained by numerical solution of the complete set of coupled differential equations which describe the population of the beam components. However, for the target thicknesses used in this experiment, these solutions differ from those obtained from Eqs. (1) and (2) by less than 3%.
26. To obtain this average we used the summary of measurements prior to 1966 given in Table III of F. J. DeHeer, J. Schutten, and H. Moustafa, *Physica* 32, 1766 (1966), (the measurement of Yu. S. Gordeev and M. N. Panov, *Soviet Physics - JETP* 9, 656 (1964), which differs markedly from the other results, was not included in the average) and the measurement by J. F. Williams and D. N. F. Dunbar, *Phys. Rev.* 149, 62 (1966).
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28. We have followed the notation of D. R. Sweetman [*Proc. Roy. Soc. (London)* A256, 416 (1960)] for the definition of σ_1 through σ_4 . We know of no common notation for the other processes.
29. Preliminary results were reported by W. G. Graham, J. W. Stearns, K. H. Berkner, and R. V. Pyle, in Electronic and Atomic Collisions, J. S. Risley and R. Geballe, eds. (University of Washington Press, Seattle, 1975), Vol. 2, p. 709; a more complete report has been submitted to *Phys. Rev. A*.

30. J. F. Williams, Ph.D. Thesis, Australian National University, 1966 (unpublished).
31. The exception to this statement is a result for σ_3 at 6 keV recently reported in Ref. 7.
32. G. W. McClure, Phys. Rev. 130, 1852 (1963).

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

<u>Authors</u>		<u>Ref.</u>	<u>Energy Range</u> (keV)	<u>Projectile</u>
Stedeford and Hasted	(1955)	2	.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	.07 - 1.05	H^+ , H_2^+
Rozett and Koski	(1968)	9	.004 - .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	.0005 - .1	H^+
Abignoli et al.	(1972)	11	.5 - 3	H^+
Dehmel et al.	(1973)	12	.08 - 2	H^0
Fournier et al.	(1974)	13	1 - 5	H^+ , H^0
Brouillard et al.	(1975)	7	6	H_2^+

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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 $\pm 5\%$.

	Energy ($\pm 4\%$) (keV)	Cross Sections (10^{-17} cm ² /atom)					
		$\sigma_{10}(\pm 4\%)$	$\sigma_{1-1}(\pm 4\%)$	$\sigma_{01}(\pm 7\%)$	$\sigma_{0-1}(\pm 7\%)$	$\sigma_{-10}(\pm 4\%)$	$\sigma_{-11}(\pm 4\%)$
incident 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
incident 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) $\pm 7\%$
b) $\pm 10\%$
c) $\pm 15\%$

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

	Energy (+ 4%) (keV)	Cross Sections (10^{-17} cm ² /atom)		
		σ_0	σ_+	σ_-
incident 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
incident 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) $\pm 7\%$

Fig. 1 Scheme of the experimental arrangement.

Fig. 2 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).

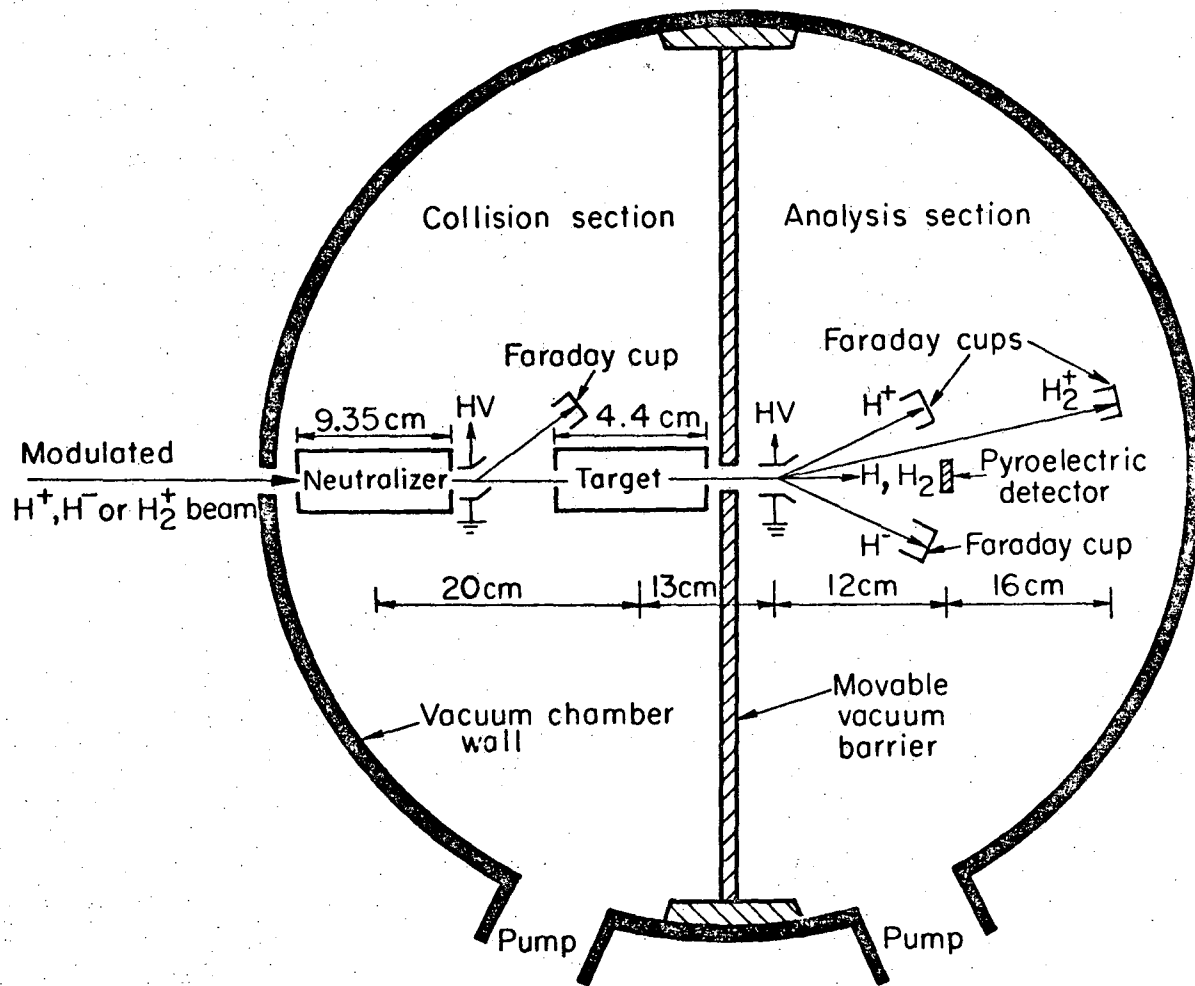
σ_{1-1} : ●, present results; ○, Williams (Ref. 5); △, Fogel et al. (Ref. 3); □, sum of partial cross sections measured by Afrosimov et al. (Ref. 8) (see text). Note: the cross sections σ_{1-1} have been multiplied by ten. The cross sections for D^+ have been plotted at one-half the D^+ energy.

Fig. 3 Cross sections σ_{01} and σ_{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 ten.

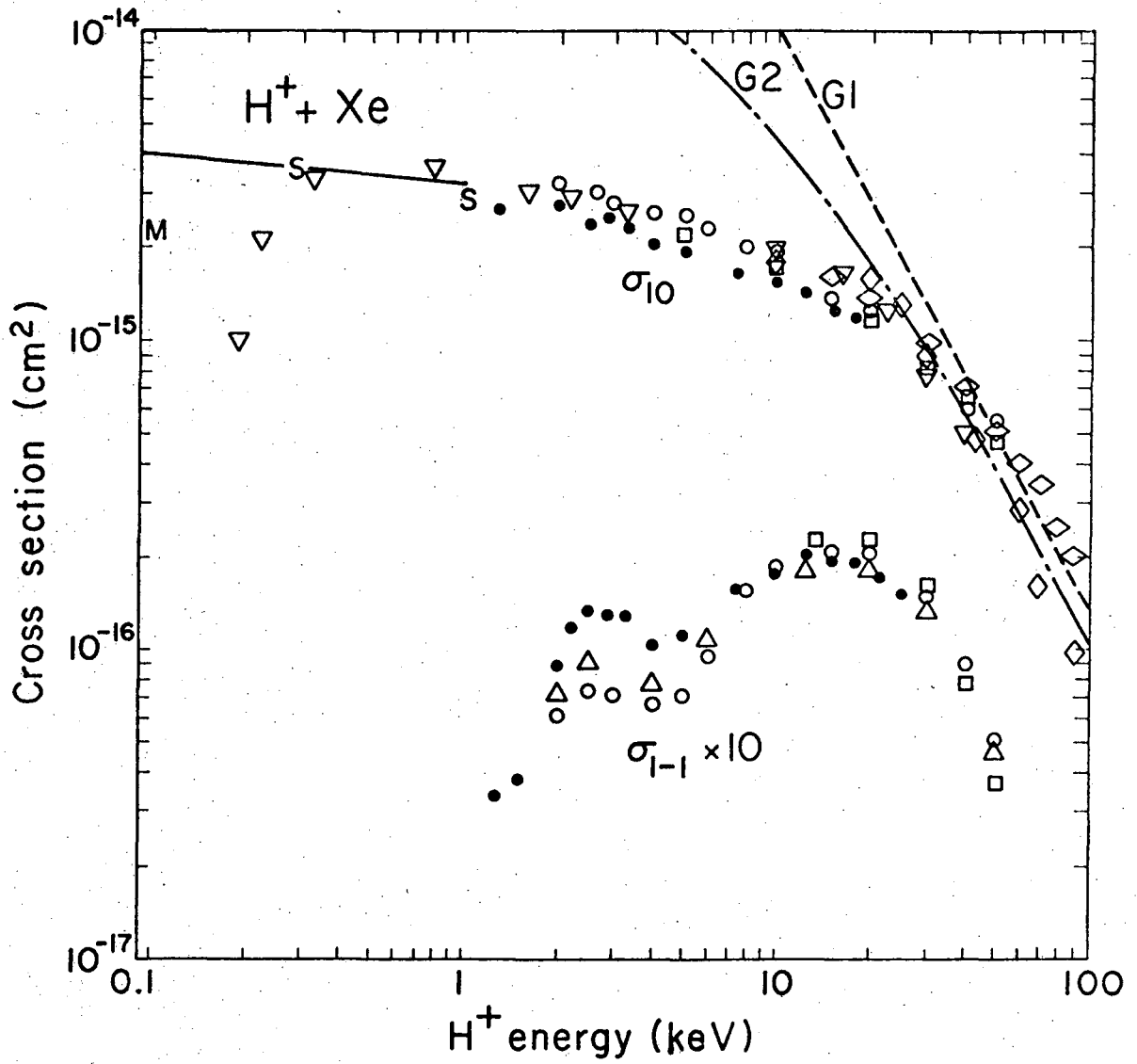
σ_{0-1} : ●, present results; ○, Williams (Ref. 5); □, sum of partial cross sections measured by Afrosimov et al.

- Fig. 3 (cont.) (Ref. 8) (see text); Δ , Fogel et al. (Ref. 3). The cross sections for D^0 have been plotted at one-half the D^0 energy.
- Fig. 4 Cross sections σ_{-10} and σ_{-11} for single- and double-electron loss for collisions of energetic H^- ions in collision with Xe gas. σ_{-10} : \bullet , present results; \circ , Williams (Ref. 5); H , Hasted (Ref. 2); ∇ , Stedeford and Hasted [$\sigma_{-10} + 2\sigma_{-11} \approx \sigma_{-10}$] (Ref. 2). σ_{-11} : \bullet , present results. The cross sections for D^- have been plotted at one-half the D^- energy.
- Fig. 5 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).
- Fig. 6 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 : \bullet , present results. " σ_{cx} " (see text): ∇ , Stedeford and Hasted (Ref. 2); —, Koopman (Ref. 14). σ_+ : \bullet , present results; \circ , Williams and Dunbar (Ref. 5). σ_- : \bullet , present results; B, Brouillard, et al. (Ref. 7). Note: the cross section σ_- has been multiplied by ten. The cross sections for D_2^+ have been plotted at one-half the D_2^+ energy.



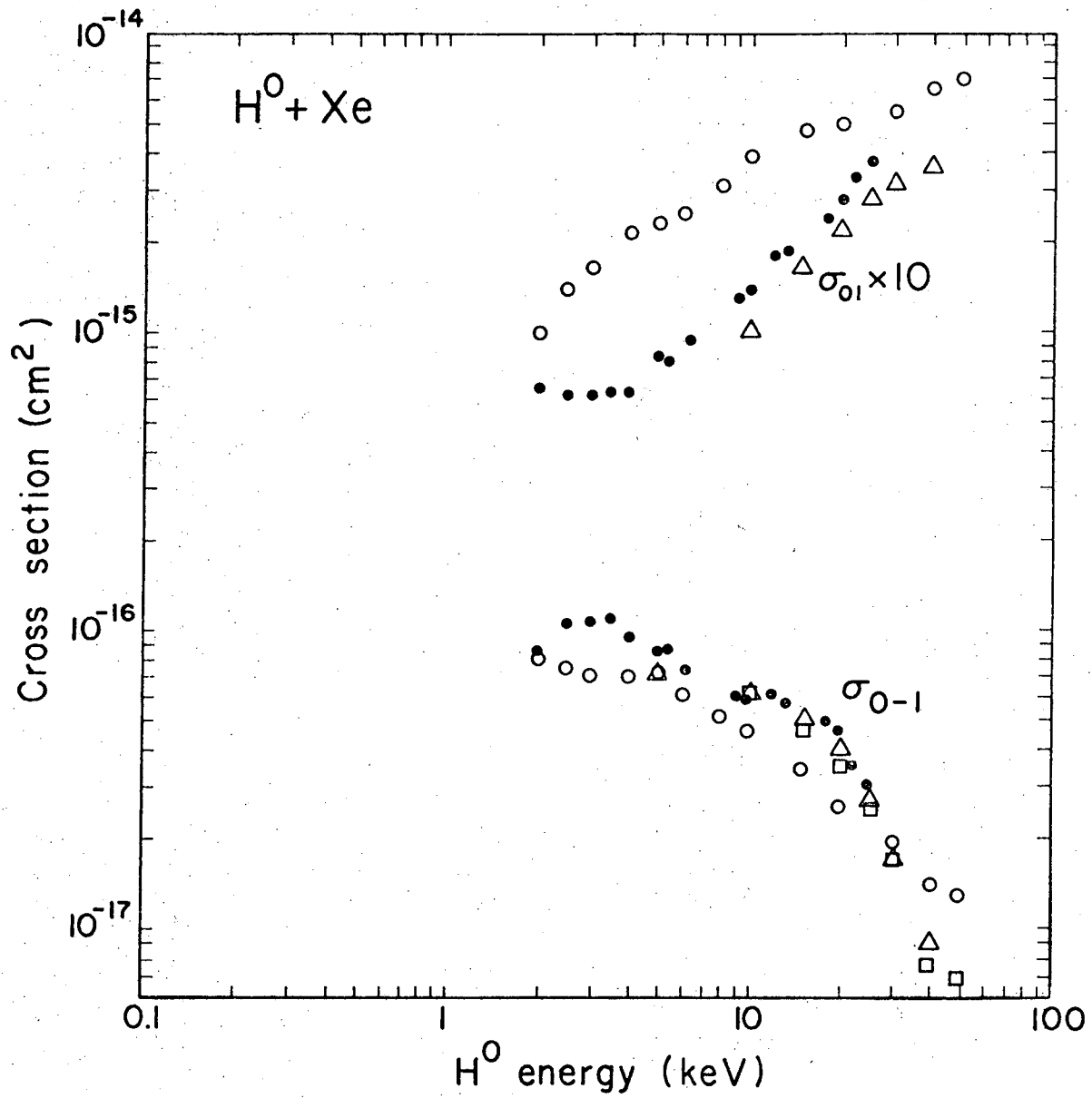
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Fig. 1



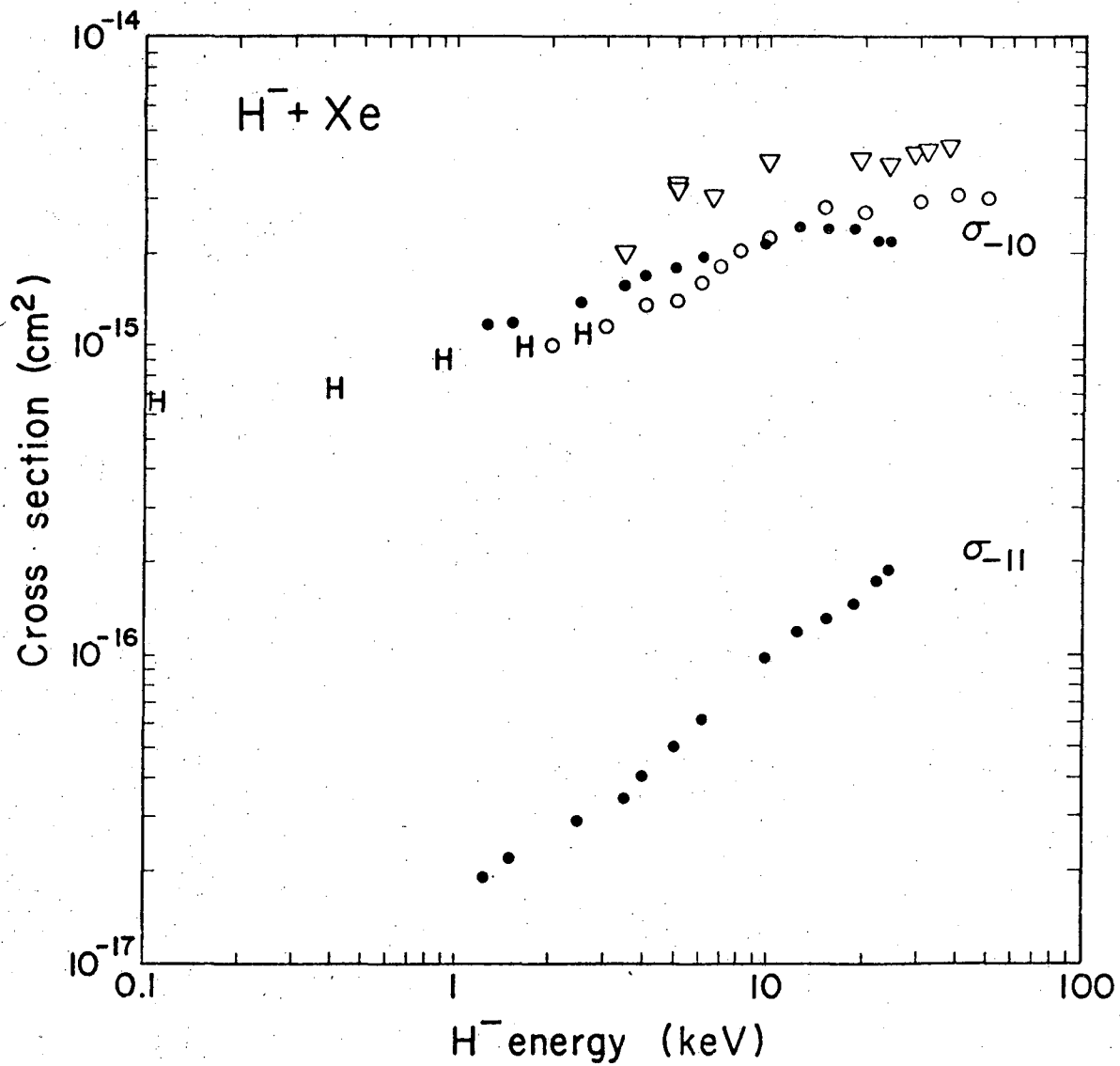
XLB 76I-2115

Fig. 2



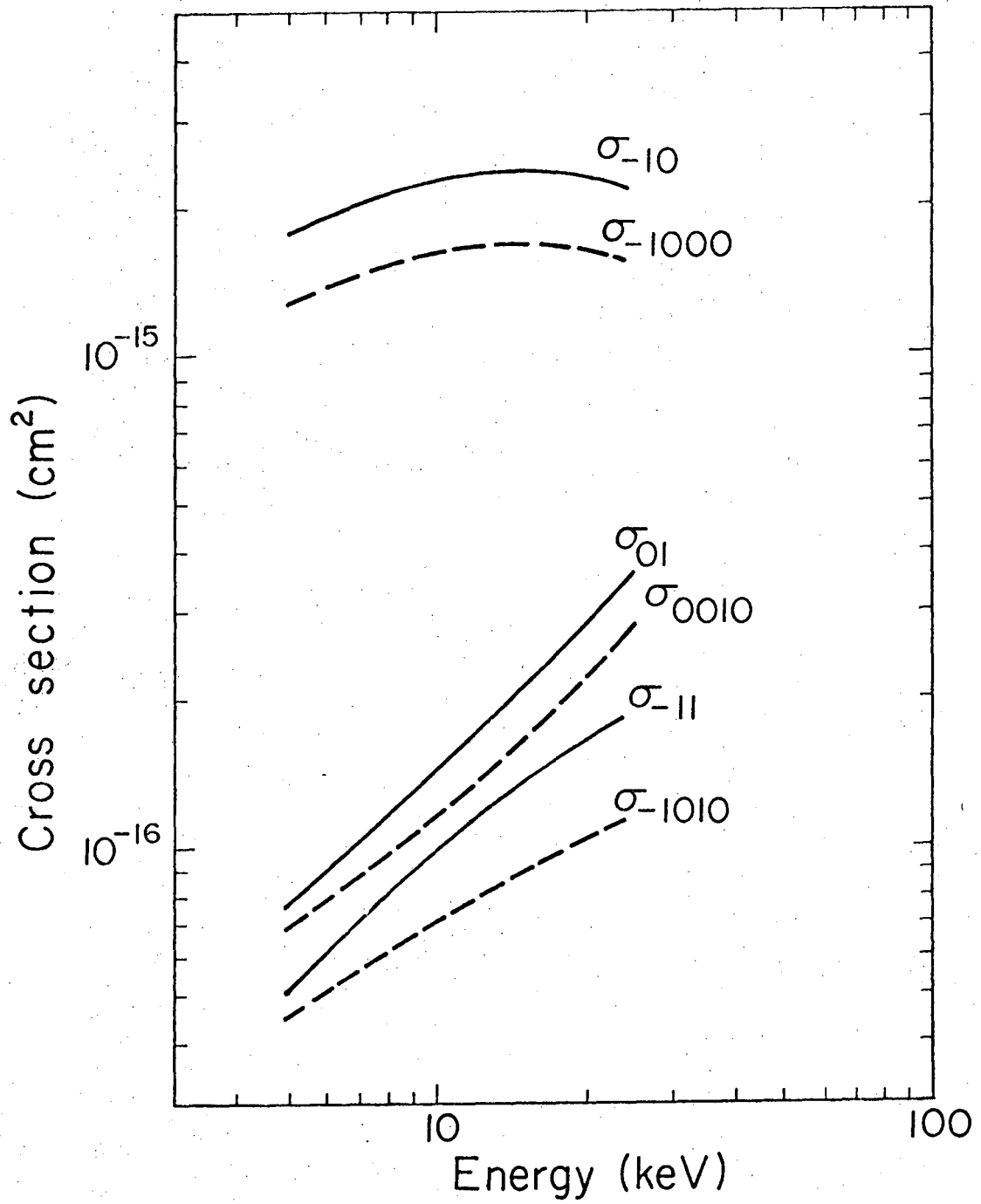
XLB 761-2116

Fig. 3



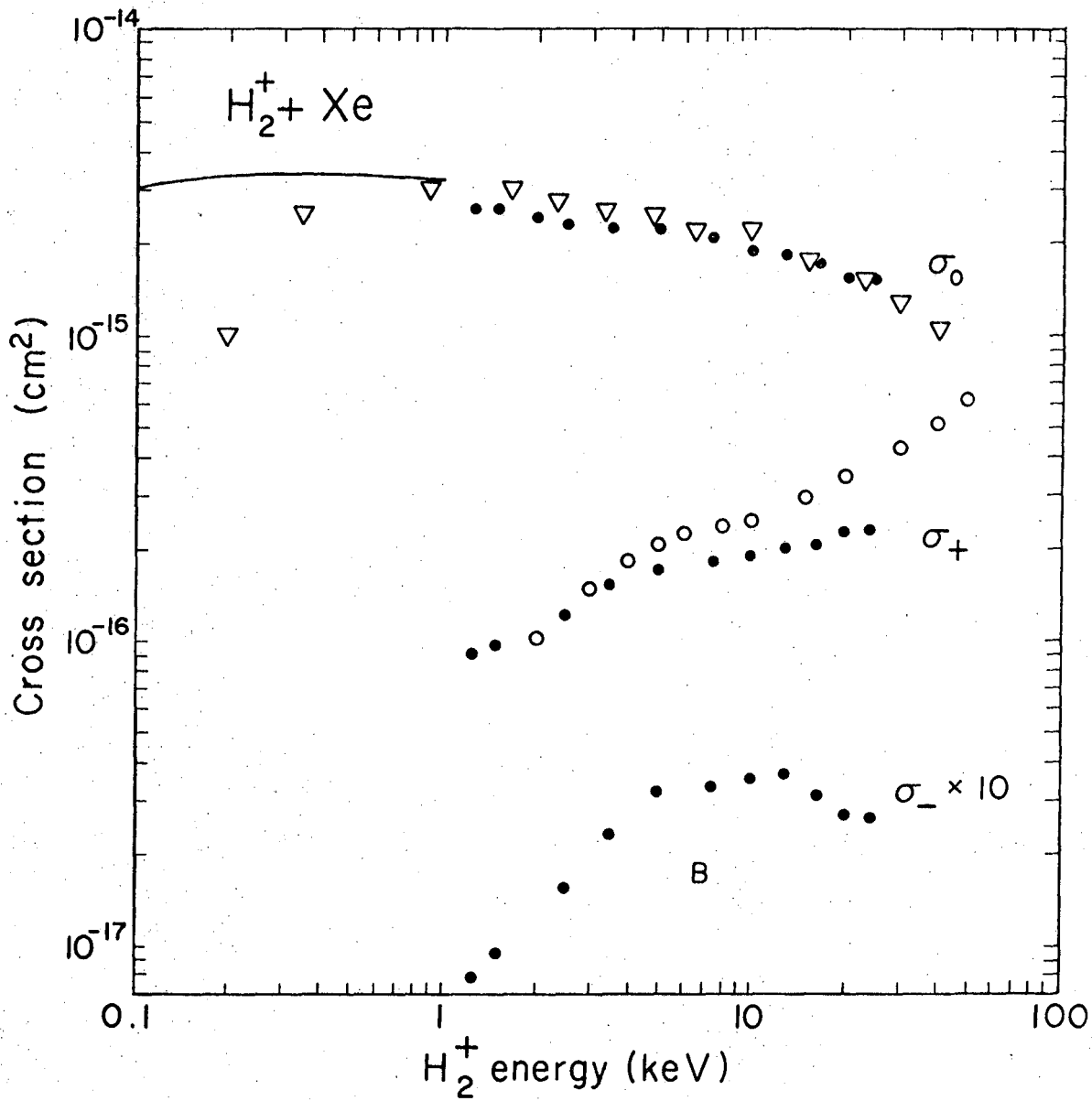
XLB 761-2117

Fig. 4



XLB 761-2118

Fig. 5



XLB 761-2114

Fig. 6

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