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Cross Sections for Positive-Ion and Electron Production in Collisions of 1–25 keV Hydrogen Atoms with Atomic and Molecular Gases*

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Cross sections are reported for production of positive ions and electrons in collisions of hydrogen atoms in the energy range 1–25 keV with He, Ne, A, Kr, Xe, H_2, and O_2. Slow positive ions are produced by capture of an electron by the fast atom from the target gas and by ionization of the target. Electrons are produced by target-gas ionization and by stripping of the fast atom. Ionization cross sections for each of the target gases are derived from the positive-ion production cross sections and previous measurements of the capture cross sections.

I. INTRODUCTION

Cross sections for charge-changing and ionizing collisions of protons and hydrogen atoms with atomic and molecular gases are useful in many applications. In space physics, for example, they are needed for calculations of ionization produced by proton auroras and for analysis of the interaction of the solar wind with planetary atmospheres. In these applications, protons collide with atmospheric constituents and produce positive ions, electrons, and energetic H^0 and H^-. At low energies, an incident proton flux is rapidly converted to an equilibrium flux of H^+, H^0, and H^- with H^0 being the primary constituent.[1] Subsequent collisions of the fast atoms with atmospheric constituents produce effects comparable in magnitude to those produced by primary protons.

Charge-changing and ionization cross sections for incident H^+ are available from several sets of measurements, which span a broad range of energies. Recent measurements and a review of previous results above 10 keV are presented in the work of De Heer *et al.*[2] Koopman[3,4] has reported cross sections for electron capture by protons at low energies and has summarized previous data. Fewer measurements have been made of cross sections for incident H^0. Williams[5] has reported capture and stripping cross sections in the range 2–50 keV and has reviewed earlier work. Ionization cross sections for incident H^0 have been measured in the range 10–180 keV by Solov'ev *et al.*[6] and in the range 150–400 keV by Puckett *et al.*[7] Electron-production cross sections for H^0 incident on several gases have been obtained in the range 50-1000 eV by Fleischmann and Young.[8,9]

In the present paper, we report measurements of the cross sections for slow positive-ion production (σ_+) and for electron production (σ_-) in collisions of 1–25 keV H^0 with H_2, O_2, and the rare gases. We have previously reported σ_+ and σ_- for H^0 incident on N_2.[10] Our present results are compared with overlapping higher-energy data[6] and with previous determinations of σ_- at 1 keV.[8,9] Ionization cross sections are derived from a combination of present results for σ_+ and previously measured capture cross sections.[5] A brief report of this work has been given elsewhere.[11]

II. EXPERIMENTAL PROCEDURE

The apparatus used to make these measurements is basically similar to that used in previous experiments in other energy ranges,[6-9] although experimental details differ from one group to another. A detailed description with a schematic diagram and an extensive discussion of the measurement techniques has been published elsewhere.[10] Only a brief description will be given here.

A low-pressure discharge in H_2 produced H^+ and H_2^+, which were extracted at probe voltages of 1–5 keV and separated by magnetic deflection. The H^+ beam was focused for maximum current at the beam detector with an einzel lens, and a gap lens was used when acceleration to energies in the range 5–25 keV was required. An H^0 beam was prepared by electron-capture collisions of the H^+ beam in a differentially-pumped gas cell with circular apertures for beam entry and exit, which also served to collimate the beam. Argon at a pressure of 2×10^{-3} Torr was used as the neutralizing gas. The measured cross sections were found to be independent of the gas used for neutralization, and the selection of argon was based only on convenience. Residual H^+ was removed from the neutral beam, and metastable H $2\,^2S_{1/2}$ atoms were quenched by an electric field in excess of 500 V/cm, the field strength which Bethe and Salpeter[12] found sufficient to quench the metastables. The measured cross sections were independent of the field strength above 500 V/cm.

The ground-state H^0 beam entered a second differentially-pumped gas cell, which contained a parallel-plate electrode system for collecting positive ions and electrons produced along a 6-cm segment of the beam track through a low-pressure target gas. The target-gas pressure was varied in the range 10^{-3} and 10^{-4} Torr and was measured by an MKS baratron.[13] Saturation positive-ion and electron currents were measured using the electrode configuration and voltages discussed elsewhere.[10] Both the positive-ion and electron saturation currents were found to be linear with pressure and beam intensity. Cross sections were obtained from the slopes of the linear plots of ion-and electron-saturation currents versus pressure at fixed-beam intensity.

The H^0 beam was detected by electron emission produced by impact of the beam with a gold-plated surface. The emission coefficient was determined at the beginning and end of each run by measuring the coefficient for a proton beam of known intensity and applying the ratio of the H^0 and H^+ emission coefficients, reported by Stier *et al.*[14] For the beam energies in this work, the ratio is nearly unity (1.1). The H^0 emission coefficient determined in this manner did not change in the time required for a cross-section measurement. Other metallic surfaces were used in preliminary experiments; although the emission coefficient for H^+ bombardment was found to be different for different surfaces, the cross sections for H^0 bombardment of the various gases did not depend on the surface used, when the above ratio and the measured coefficient for H^+ were used to calculate the H^0 beam intensity.

The precautions used to guard against emission of electrons, from interior surfaces of the collision chamber struck by the energetic beam and from collisions of the collected ions and electrons with the electrode system, have already been described.[10] No changes from the previous techniques were necessary. In the present thin-target experiments, the effective collision path length, when the ion or electron currents are saturated, is just the length of the collector electrode, which is directly connected to an electrometer and surrounded by grounded guard plates.

The diameters of the collision-chamber exit aperture and the beam-detector entrance aperture were larger by 30 and 100%, respectively, than the calculated beam sizes at the location of those apertures. As described before, however,[10] these apertures could be insulated from ground and positive currents on them caused by H^+ impact, or ejection of electrons by H^0 impact could be measured. After alignment of the apparatus, no such currents were found, and we conclude that all of the beam that entered the collision chamber passed through it to the detector. Attenuation of the beam by target-gas scattering was negligible at the low pressures used in these experiments.

For comparison of our charge-collection and pressure-measuring techniques with those of other investigators, measurements were made at 10 and 15 keV of σ_+ and σ_- for proton bombardment of the gases used in this work. The results of this comparison for N_2 over the full-energy range of our apparatus are available elsewhere. For the electron-capture cross section σ_{10} above 10 keV, our results for N_2 were in very good agreement with those of De Heer *et al.*,[2] and at 1 keV similarly good agreement with Koopman's results was found.[4] In the present work, we again found good agreement with previous measurements of σ_{10}. This cross section is obtained in charge-collection experiments by subtracting σ_- from σ_+. Above 10 keV, De Heer *et al.*[2] have found that this method of obtaining σ_{10} agrees well with previous measurements using beam-attenuation techniques. The various measurements in charge-collection experiments of σ_- have differed, however, by more than stated experimental errors. Our results for σ_- were within 10% of the values reported by De Heer *et al.*[2]

Several measurements of σ_+ and σ_- for H^0 bombardment were made at various beam energies in the range 1-25 keV. The average values are given below. The average deviation of the results was less than 10%, except below 2 keV, where average deviations were sometimes found to be 15%. A source of possible systematic error is in the value of 1.1 for the ratio of the H^0 to H^+ electron emission coefficients for the gold-plated surface in the beam detector. Amme[15] has summarized studies of this ratio and has discussed the mechanism of secondary electron emission.

We estimate that the maximum error caused by adoption of the above ratio is $\pm 10\%$. We do not find variations in σ_+ and σ_- that exceed the average deviation of results for one surface, when different surfaces are used in the beam detector. In Sec. III, we compare present results with other data obtained at the extremes of our energy range with different H^0 beam-detection techniques. At 1 keV, differences with previous data[8,9] do not exceed our systematic error estimate, and similar pressure-measurement and charge-collection techniques were used. Above 10 keV, agreement is good for Ar and H_2, but discrepancies are as large as 30% for Ne and Kr. The variation in the discrepancy from one gas to another suggests that different pressure-measuring techniques account for at least some of the differences at high energy.

III. EXPERIMENTAL RESULTS

Results for σ_+ and σ_- for the rare gases H_2 and O_2 are displayed in Figs. 1–7 and compared with previous results, where available. In Fig. 1, results are shown for He in the energy range 0.1-100 keV. Our result for σ_- is within 10% of the value reported by Fleischmann and Young[8] at 1 keV. In the energy range 10–25 keV, however, the results for σ_- are about 20% lower than the results of Solov'ev *et al.*[6] For σ_+ the present results are 10–20% lower than their values. Fleischmann and Young[8] estimate a maximum error of 10–15% and Solov'ev *et al.*[6] give their results as accurate to within 15%. Below 3 keV, the measurement of σ_+ for He presents special experimental problems. The cross section is so low that, even for an initially pure gas sample, a low level of an impurity with a large σ_+ such as N_2, which can outgas from the walls of the gas feed line, can lead to erroneously high values for the apparent positive-ion-production cross section. The background positive-ion current due to ionization of residual gas in the collision chamber also becomes too high for an accurate cross-section measurement.

Positive ions are produced in ionization and capture reactions as follows:

$$H + M \rightarrow H + M^+ + e \qquad (1)$$

and

$$H + M \rightarrow H^- + M^+. \qquad (2)$$

Electrons are produced by target-gas ionization,

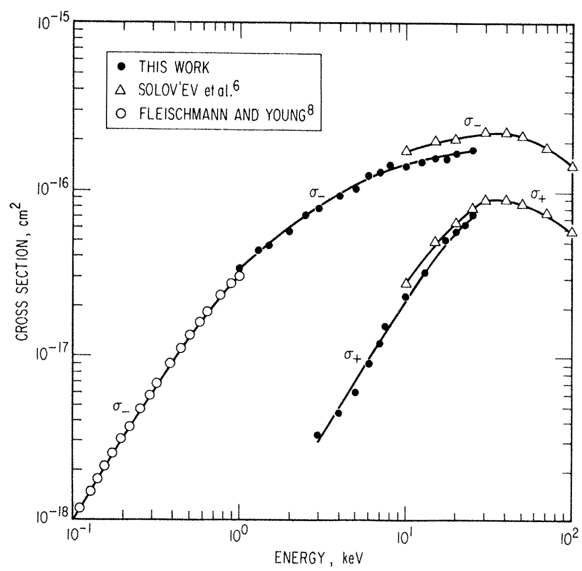

FIG. 1. Cross sections for positive-ion (σ_+) and electron production (σ_-) in collisions of 0.1–100 keV H^0 with He.

as in reaction (1), and by stripping

$$H + M \rightarrow H^+ + M + e \quad . \qquad (3)$$

The cross sections σ_+ and σ_- are sums of all cross sections for processes which produce positive ions and electrons, respectively. More complex processes than the above also contribute to the charge-production cross sections, although at the low energies used in this work, processes (1)–(3) are the major contributors to σ_+ and σ_- for each target gas M. Solov'ev *et al.*[6] used the charge-collection technique employed here, but they reported σ_{01}, which in their energy range (10–180 keV), is essentially $\sigma_- - \sigma_+$. For comparison with the present σ_- results, we have added their σ_+ and σ_{01} values to obtain their σ_- results.

The Russian workers[6] used a thermistor to measure the neutral-beam intensity, whereas Fleischmann and Young[8,9] employed their previous measurements [16] of the angular distribution of fast H^0 produced by capture collisions of H^+ with their neutralizing gas O_2. The agreement between our high-energy and low-energy data and these previous results obtained with different beam detectors is quite good. Data are now available for cross sections for charge production in collisions of H^0 with He that cover a broad energy range with an accuracy sufficient for most applications.

In Fig. 2, data are shown for σ_+ and σ_- for H^0 on Ne. Agreement with Fleischmann and Young's data at 1 keV is nearly exact. Both σ_+ and σ_- are

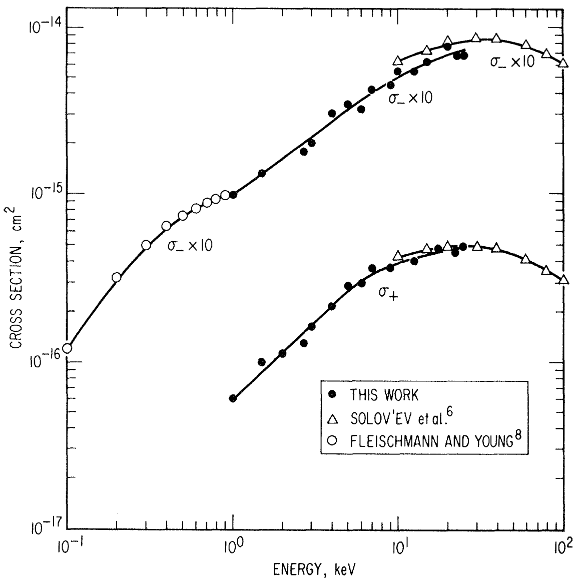

FIG. 3. Cross sections for positive-ion (σ_+) and electron production (σ_-) in collisions of 1–25 keV H^0 with Ar.

lower, however, by about 30% than the results of Solov'ev *et al.* at energies above 10 keV.[6] The slow decrease in the average value of σ_+ below 2 keV was reproduced in many measurements. Such an effect could arise in a gas with a low-ionization cross section either from an impurity with a large ionization cross section or from a large capture cross section of the target gas at low energies. Ne, apparently, does not have a large capture cross section at low energies,[5] and no outgassing impurity was apparently present, since repeated heating as well as shortening of the gas-feed lines resulted in no change in the cross section. Several different samples of high purity Ne were tried with identical results. Thus, the ionization cross section, itself, may show an unusual energy dependence at low energies. Gilbody and Hasted[17] have found such an effect below 10 keV for ionization of Ne by protons. Estimated errors at low energy are shown for this unusual case on the figure.

Data for Ar are shown in Fig. 3. Agreement with Solov'ev *et al.*[6] is better above 10 keV for Ar than for Ne. At 1 keV, the present value of σ_- agrees well with that reported by Fleischmann and Young,[8] but the energy dependence found above 1 keV does not fit smoothly onto the energy dependence that they found below 1 keV.

The present values of σ_+ and σ_- for Kr and Xe are plotted in Figs. 4 and 5. For Kr the data above 10 keV are lower by 30% than the results of Solov'ev *et al.*[6] There are no previous high-energy data for Xe, nor any low-energy data for either Kr or Xe.

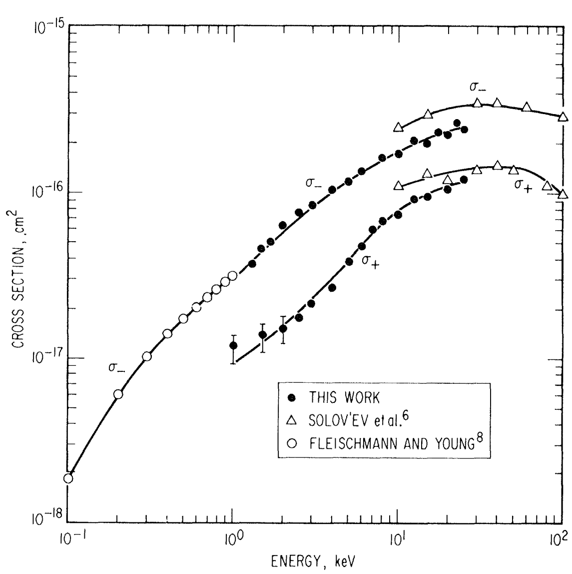

FIG. 2. Cross section for positive-ion (σ_+) and electron production (σ_-) in collisions of 0.1–100 keV H^0 with Ne.

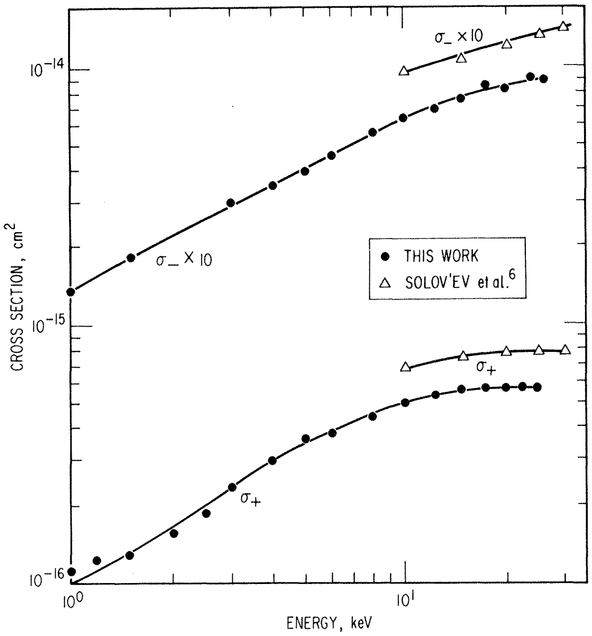

FIG. 4. Cross sections for positive-ion (σ_+) and electron production (σ_-) in collisions of 1–30 keV H^0 with Kr.

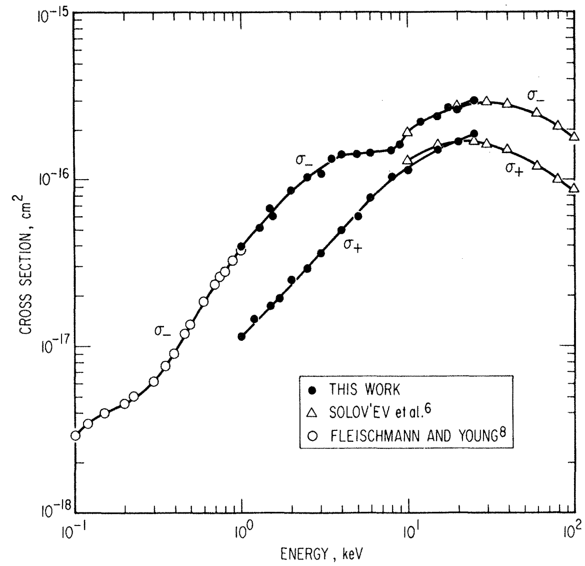

FIG. 6. Cross sections for positive-ion (σ_+) and electron production (σ_-) in collisions of 0.1–100 keV H^0 with H_2.

Cross sections for H_2 are shown on Fig. 6. Both σ_+ and σ_- are in very good agreement with the results of Solov'ev *et al.*[6] above 10 keV, and σ_- at 1 keV agrees well with Fleischmann and Young's value at 1 keV.[8] The results for σ_- indicate structure in the range 4–8 keV. This is due to the structure in the stripping cross-section energy dependence that has been found previously.[5] σ_- also displays a structured energy dependence below 1 keV.[8] The ion-production cross section, which is primarily composed of the total-ionization cross section for H^0 incident on H_2, does not show this structure.

For O_2, σ_- and σ_+ are plotted in Fig. 7. Here

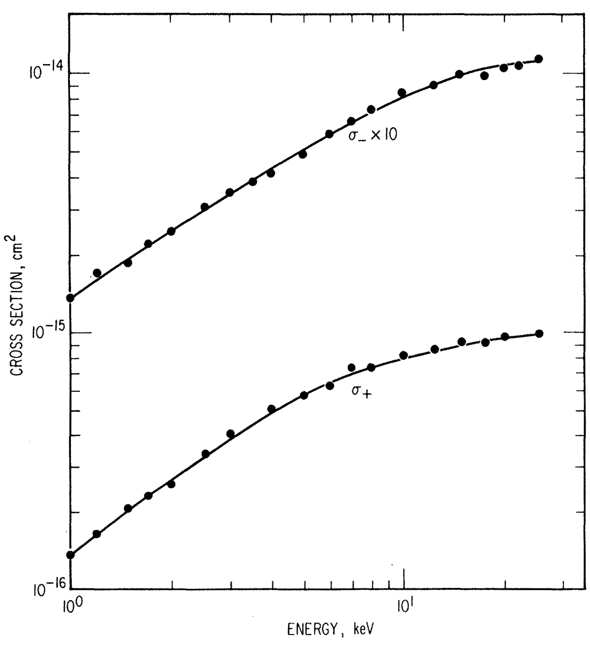

FIG. 5. Cross sections for positive-ion (σ_+) and electron production (σ_-) in collisions of 1–25 keV H^0 with Xe.

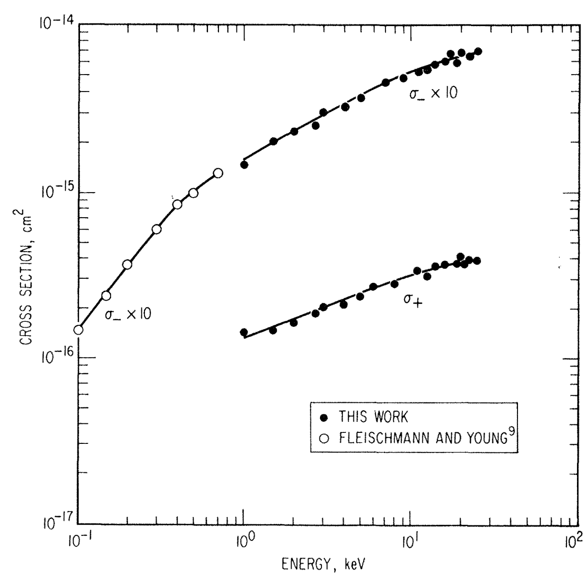

FIG. 7. Cross sections for positive-ion (σ_+) and electron production (σ_-) in collisions of 0.1–25 keV H^0 with O_2.

again, the results near 1 keV are in good agreement with previous low-energy measurements.[9] There are no previous data at higher energies.

The charge-production cross sections are directly useful in many applications, but the total ionization cross section is of more interest theoretically and can be derived from the charge-production cross sections when the capture and stripping cross sections are known, because

$$\sigma_i = \sigma_+ - \sigma_{0-1} \qquad (4)$$

and $\sigma_i = \sigma_- - \sigma_{01}$, (5)

where σ_i is the total ionization cross section, σ_{0-1} is the capture cross section, and σ_{01} is the stripping cross section. σ_{01} and σ_{0-1} have been measured most recently by Williams[5] for H^0 incident on H_2 and the rare gases in the energy range 2-50 keV.

At energies above 10 keV the capture cross sections are small compared to σ_+, and differences among the various reported values do not

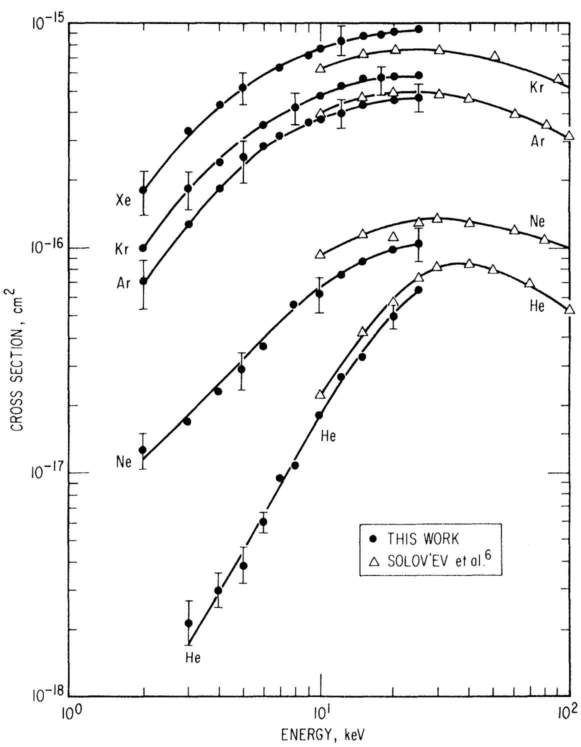

FIG. 8. Cross sections for ionization of rare gases by collisions with 2–100 keV H^0. The cross sections were derived by subtracting the electron-capture cross section σ_{0-1} obtained in other experiments, from values of σ_+ obtained in this work and by Solov'ev *et al.*[6] The error bars on various points in the figures are the variances which result from the subtraction of the two cross sections, which are each uncertain by 10–15%.

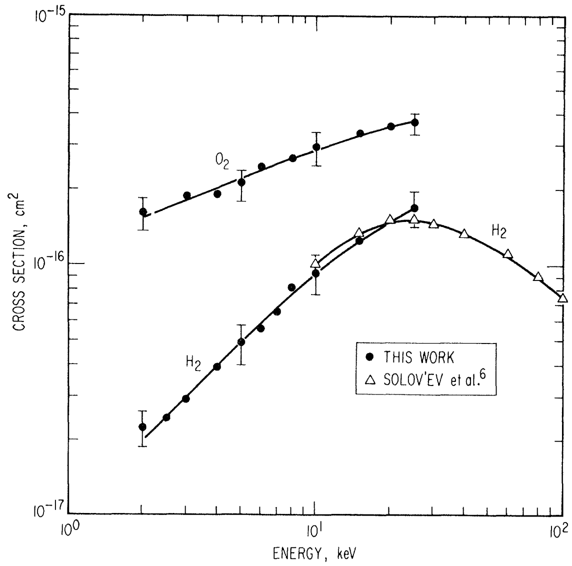

FIG. 9. Cross sections for ionization of H_2 and O_2 by collisions with 2–100 keV H^0. The cross sections and the error bars were determined in the same manner as for the rare gases (see Fig. 8).

significantly affect values of σ_i derived from Eq. (4). At low energies the capture cross sections are small compared to σ_+ for Ne, H_2 and O_2, but for other gases σ_{0-1} accounts for as much as 30% of σ_+. The stripping cross sections, on the other hand, are significant fractions of σ_- at most energies for all of the gases. Eq. (5) is less useful than Eq. (4) for obtaining the ionization cross sections.

In Figs. 8 and 9, we have plotted the total ionization cross sections, which result from application of Eq. (4) with the present values of σ_+ and Williams's results[5] for σ_{0-1}, except for O_2, for which data of Stier and Barnett[18] were used, with an extrapolation from their low-energy limit of 4 to 2 keV. For H^0 on H_2, McClure[19] has also measured σ_{0-1} at energies as low as 2 keV. His results at low energies are higher, by about a factor of 2, than those of Williams. For H_2, σ_{0-1} at low energies is very small compared to σ_+, and the discrepancy in σ_{0-1} affects σ_i by only about 10%. The error bars at some points on the figures indicate only the expected variance, which results from subtracting σ_{0-1}, as measured by Williams with a stated error of 10%, from our values for σ_+ with an average deviation of 10-15%. For the heavier rare gases, which have larger cross sections, and for He, for which both σ_+ and σ_{0-1} are small, a larger error would result if Williams's results are systematically too low. The correct values of σ_i would then be lower at low energies than indicated on the figures.

For H_2, σ_+ is larger than σ_{0-1} at 2 keV by a factor of 10, and σ_i is affected very little by discrepancies in σ_{0-1}. At 2 keV, σ_i is 2.3×10^{-17} cm^2, to within 10-15%; σ_- is 8.5×10^{-17} cm^2. From Eq. (5), we find that σ_{01} is 6.2×10^{-17} cm^2. This agrees very well with McClure's result[19] and is higher than Williams's value (4×10^{-17} cm^2).[5] Because of the uncertainties in σ_+ and σ_- the value of the stripping cross section is uncertain to within about 20%. For cases in which σ_+ and σ_- are comparable, the errors in σ_{01} would be larger than this, and we have not, in general, attempted to derive stripping cross sections from Eq. (5). For He at 3 keV, however, σ_i is $1.7\text{-}2.7\times10^{-18}$ cm^2 and σ_- is 8×10^{-17} cm^2. Thus, we find that σ_{01} is $8\pm1\times10^{-17}$ cm^2, allowing for a 15% deviation in σ_-. Williams[5] finds it to be $8\pm0.8\times10^{-17}$ cm^2, which is in good agreement with the present result. Ne is the only other gas for which the expected error in σ_{01} is not much greater than 20%. We find $\sigma_{01}=5.8\times10^{-17}$ cm^2, while Williams[5] finds it to be 4.3×10^{-17} cm^2 at 2 keV.

The above data indicate that, for cases in which a reasonably accurate stripping cross section can be derived from our charge-collection experiments, the results at 2 keV are higher than those reported by Williams,[5] but for He, agreement is good at 3 keV. Further measurements of σ_{01} and σ_{0-1} at low energies would be useful in resolving the discrepancy at 2 keV.

IV. DISCUSSION

At high energies, protons and electrons of comparable velocities have cross sections for target-gas ionization that are close in magnitude and that follow the asymptotic $aE^{-1}\ln bE$ energy dependence given by the Bethe-Born approximation. Puckett *et al.*[7] find a similar energy dependence for ionization by incident H^0 and have used the concept of an effective charge for H^0 and H^+ in the point-charge ionization problem. The effective charge for H^0 is about $\frac{2}{3}$ of the effective charge for H^+.

At low energies the adiabatic criterion can be applied to predict the increase in ionization cross sections from threshold to a broad peak in the keV energy regime. This criterion, however, provides no means of calculating the maximum cross section. In view of the lack of a satisfactory theoretical treatment of the ionization processes at low energies, a semiempirical approach to the development of analytical expressions, which represent the cross sections over a broad range of energies and which are useful in applications, is appropriate. Green and McNeal[20] have developed such formulas for ionization and charge-changing collisions involving H^+ and H^0 and have attempted to relate parameters in the formulas to properties of the atomic gas, such as ionization potentials and atomic numbers. The formulas have the asymptotic energy dependence at high energies given by the Bethe-Born approximation.

Fleischmann and Young[8,9] found that when their σ_- results below 1 keV were smoothly extrapolated to higher energies, the resulting curves appeared to be simple multiples of the σ_{01} curves for He, Ne, Ar, H_2, N_2 and O_2. They suggested that a uniform trend of σ_i/σ_{01} with E_i-E_H, where E_i is the ionization potential of the target and E_H is the ionization potential of H^0, was indicated. Errors in σ_i/σ_{01} can arise in the extrapolation of the σ_- curves to higher energies and in the subtraction of σ_{01} from σ_- to obtain σ_i. With the present values of σ_i, obtained in the more accurate subtraction of σ_{01} from σ_+, it is possible to test the suggested trend of σ_i/σ_{01} with E_i-E_H.

In Table I, the values of σ_i/σ_{01} are given at 5, 10, 15, and 25 keV. For N_2, the results for σ_i reported elsewhere[10] have been used. Williams's results[5] for σ_{01} for H_2 and the rare gases have been used. As indicated above, these results may be low at the lowest energy, which would cause the value of σ_i/σ_{01} to be too large. For O_2 and N_2, Stier and Barnett's values[18] have been used for σ_{01}. E_1-E_H is tabulated, as are values of the polarizabilities of the target gases.[21] For some of the gases σ_i/σ_{01} is strongly energy dependent. Small values of σ_i/σ_{01} at low energies appear to be better correlated with low target-gas polarizabilities than with high target-gas ionization potentials. A simple trend of σ_i/σ_{01} with E_i-E_H is not evident.

TABLE I. Ratios of ionization and stripping cross sections at various beam energies for atomic and molecular targets. The differences in ionization potentials of the target gases and H^0 (E_i-E_H) and the polarizabilities α of the target gases are also given.[21]

Beam energy (keV)	5 σ_i/σ_{01}	10 σ_i/σ_{01}	15 $\sigma_i/_{01}$	25 σ_i/σ_{01}	α (Å^3)	E_i-E_H (eV)
He	0.04	0.14	0.30	0.64	0.206	11
Ne	0.33	0.45	0.53	0.53	0.408	8
Ar	1.9	1.8	1.6	1.3	1.64	2.2
Kr	2.1	1.5	1.4	1.2	2.49	0.3
Xe	2.1	2.0	1.8	1.8	4.02	−1.5
H_2	0.76	1.3	1.4	1.2	0.806	2.2
O_2	1.4	1.3	1.3	1.2	1.57	−1.5
N_2	1.1	1.0	1.0	0.9	1.74	2.1

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