INFORMATION TO USERS

The most advanced technology has been used to photograph and reproduce this manuscript from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI
University Microfilms International
A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
313/761-4700  800/521-0600
Absolute differential cross sections for electron capture and loss by keV hydrogen atoms

Smith, Gerald J., M.A.

Rice University, 1990
RICE UNIVERSITY

ABSOLUTE DIFFERENTIAL CROSS SECTIONS FOR ELECTRON CAPTURE AND LOSS BY keV HYDROGEN ATOMS

by

Gerald J. Smith

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF ARTS

APPROVED, THESIS COMMITTEE:

R. F. Stebbings
Professor of Physics and of Space Physics and Astronomy
Chairman

R. G. Hulet
Assistant Professor of Physics

P. M. Stevenson
Associate Professor of Physics

Houston, Texas
February, 1990
Abstract

Absolute Differential Cross Sections for Electron Capture and Loss by keV Hydrogen Atoms

by

Gerald J. Smith

Absolute differential cross sections for electron capture and loss by neutral hydrogen atoms incident on various gases are presented. The measurements cover a laboratory angular range of 0.02° to 1.77° and a laboratory energy range of 2.0 to 5.0 keV. The target gases include H₂, O₂, N₂, Ar and He. Integrated experimental cross sections are compared with total cross sections reported by other investigators.
Acknowledgements

I would like to express my gratitude to the many people whose contributions made this experiment possible. I owe thanks to my thesis advisor Dr. R.F. Stebbings for his guidance and for the opportunity to participate in this research. I greatly appreciate the daily advice and ideas given to me by Dr. K.A. Smith, whose experience helped me to overcome many obstacles. It was also a great help to be able to work closely with people in an atmosphere of cooperation and friendliness. For this I owe my thanks to postdocs Lee Johnson and Ru-Shan Gao and to Dave Schaffer, Charlie Hakes, Pascal Renault and Dean Sieglaflf, all of whom in some way contributed to this experiment.

Certainly not least of all, I owe my thanks to my parents and family, without whose limitless support and patience I would not have made it to where I am today. No amount of thanks here is enough.

This research has been supported by the National Aeronautics and Space Administration, the National Science Foundation, and the Welch Foundation.
# TABLE OF CONTENTS

**CHAPTER I.** INTRODUCTION  

**CHAPTER II.** EXPERIMENTAL METHOD  
- Apparatus  
- Detector Design and Operation  
- Cross Section Determination  
- Detector Calibration  
- Measured Quantities  
- Data Accumulation  
- Data Analysis  
- Corrections to Data  

**CHAPTER III.** RESULTS AND DISCUSSION  

REFERENCES
Introduction

Neutral hydrogen atoms incident on various target gases may undergo charge changing through a variety of channels. Processes for the production of fast protons or H\(^-\) ions are:

- **Electron Loss**: \( H + X \rightarrow H^+ + X + e^- \)  \( (1) \)
- **Electron Loss**: \( H + X \rightarrow H^+ + X^- \)  \( (2) \)
- **Electron Capture**: \( H + X \rightarrow H^- + X^+ \)  \( (3) \)

where multiple ionization, excitation, and target dissociation are ignored. Note that reaction (2) does not occur for some targets.

Measurements of absolute differential cross sections for electron loss (stripping) and electron capture (attachment) of neutral hydrogen atoms are of interest in studying the upper atmosphere. Fast neutral hydrogen atoms are present in the upper atmosphere as a result of charge exchange of ring current protons trapped in the earth's magnetic field. These magnetic field lines converge as they descend to lower altitudes near the earth's poles. As trapped ions spiraling along the field lines at high altitudes (where there are few other particles with which to collide) travel towards lower altitudes, they are mirrored by the converging field lines. During periods of geomagnetic disturbance caused by solar flares, the earth's magnet field may become distorted, allowing these ions to penetrate lower into the atmosphere than they normally do and encounter higher atmospheric gas densities. Charge exchange in collisions with atmospheric species (mostly O and N\(_2\)) convert the precipitating protons to fast neutral hydrogen atoms which are not confined by the magnetic field. The direction of a proton's velocity vector at the moment of a neutralizing collision can be towards earth, out into space, or anywhere in between since the proton spirals along the magnetic field lines. Thus some of the fast neutrals produced
will be directed towards regions of higher gas densities where they may undergo further collisions. In the energy range below approximately 30 to 40 keV$^{12}$, the charge changing process by which fast incident protons are neutralized takes place with a greater efficiency than the reverse process of ionization of fast neutral hydrogen atoms. As a result, protons which become neutralized through collisions spend a substantial amount of time as fast neutral hydrogen atoms before undergoing subsequent collisions resulting in re-ionization$^1$.

Collisions of precipitating protons, H$^-$ ions, and hydrogen atoms with atmospheric species produce auroral phenomena such as ionization and light emission, which have been the subject of many investigations. In order to model and more fully understand these phenomena, it is necessary to know the relative fractions of H$^+$, H$^-$, and H participating in these reactions, which in turn requires a knowledge of, among other things, the stripping and attachment cross sections for H atoms incident on the major atmospheric constituents. The stripping cross section also provides information on the production of free electrons, which in turn affects the chemistry of the auroral regions. Although several measurements of these cross sections have been made over the last thirty years, there is wide disagreement between individual measurements. There is also a total lack of detailed differential measurements below scattering angles of one degree where substantial percentages of the total cross sections lie. Differential measurements have been reported by several investigators$^{2,3,4,5}$, but none of these exhibit sufficient resolution at smaller angles to determine what structure, if any, is present.

In an effort to satisfy this need, this thesis reports absolute differential cross section measurements for stripping and attachment of hydrogen atoms incident upon Ar, He, H$_2$, O$_2$, and N$_2$. Measurements are provided over the 2.0 to 5.0 keV energy range, with a laboratory angular range of 0.02 to 1.77 degrees (in some cases this range is narrower for attachment data) and an angular resolution of 0.02 degrees.
Experimental Method

Apparatus

In order to measure the processes (1) through (3) for the production of fast H\(^+\) and H\(^-\) ions, a fast neutral hydrogen beam must be formed in the apparatus. A schematic diagram of the apparatus used is shown in figure 1. Ions are produced in a hot cathode, low pressure, magnetically confined plasma ion source, which is maintained at a potential equal to the desired energy of the ion beam. The ions emerging from the source pass into a three element Einzel lens where they are both accelerated to their final energy and focused. At this point, several species of ions exist in the beam, which passes into the first of two 60° sector magnets. Tuning of the magnetic field intensity allows for the selection of the charge to mass ratio of the desired ionic species. Before entering the second magnet, the beam passes through an electrostatic field created by a pair of deflection plates. By applying voltages to these plates the beam can be further deflected and focused in the vertical direction. Focusing in the horizontal direction takes place in the magnets. Although no detailed energy analysis is performed on the beam, tests performed by varying the beam defining voltage indicate that the maximum particle energy range that can pass through the combination of magnets and collimating apertures is on the order of 15 eV's. Thus, in the worst case the energy spread in the beam entering the target gas cell is less than ±0.4% of the total beam energy, regardless of the energy spread in the beam leaving the source.

After passing through the second magnet, the ions enter a charge-transfer cell (CTC) containing krypton gas as a neutralizing agent for the protons. Krypton was selected because its first ionization potential energy (13.996 eV) is close to that of hydrogen. Since the difference in the ionization energies of krypton and hydrogen is so small, the
CTC exit aperture = .010 mm diam.
TC entrance aperture = .020 mm diam.
TC exit aperture = .400 mm diam.
TC length = 2.60 mm

PSD1 = 25 mm diam. active area
PSD2 = 40 mm diam. active area

Figure 1. Stripping/Attachment apparatus and useful dimensions.
charge transfer cross section can be expected to be both large and strongly forward peaked. This is in fact the case, as demonstrated by previous measurements done in this research group. This large cross section provides for a relatively high flux (particles per second) of neutral hydrogen leaving the CTC, and the forward peaked distribution allows more of these atoms to pass through the beam-collimating apertures. The first of these apertures is 10 μm in diameter and defines the exit of the CTC through which the beam must pass. Immediately after the CTC, a strong electric field (on the order of 400 V/cm) is applied to a pair of deflection plates (DP1). This field serves to both remove unneutralized protons from the beam as they leave the CTC, and to de-excite metastable excited-state H(2s) from the beam via Stark mixing of the H(2s) and H(2p) levels. In such a field, calculations show that the lifetime for de-excitation from H(2p) to H(1s) is 3.2 x 10^{-9} seconds, which is double that for a field free region. However, the field reduces the lifetime associated with the H(2s) to H(1s) transition from 0.14 seconds (for a field free region) to approximately 3.2 x 10^{-9} seconds, equal to that for the H(2p) to H(1s) transition. With a maximum beam velocity under 10^8 cm/sec, there is time for about 95% of the metastable H(2s) state atoms to de-excite in the approximately 10^{-8} seconds that the beam atoms spend in the electric field. Further, it is expected that there is a decrease in the cross sections for production of excited states with increasing n. Verification of this trend (albeit at slightly higher energies) is found in experimental cross section measurements. Collimation of the atomic beam also discriminates somewhat against these excited states due to the larger scattering angles associated with the non-resonant excitation collisions. For very high principal quantum number the longer lived Rydberg states are ionized by the quenching field, but there is a range of lower principal quantum numbers for which the Rydberg atoms are not ionized and could survive to reach the target cell. It is not expected, however, that a significant fraction of the incident protons will capture electrons into these states.
Approximately 19 cm beyond the CTC is the target cell containing the target gas. Shielding was placed in the apparatus coplanar with the entrance to the TC to prevent deflected protons or other particles scattered away from the beam axis from reaching the end of the vacuum chamber containing the detectors. Beam atoms enter the TC through the second collimating aperture which has a diameter of 20 μm. Combined with the 10 μm aperture of the CTC, the maximum beam divergence allowed by this geometry is 0.009°. This tight beam collimation together with the short length of the TC (see figure 1) results in a very small and well defined scattering volume which is necessary for high angular resolution in the scattering signal. The tight collimation also has the effect of reducing the beam intensity to such a small value that the average distance separating primary beam atoms entering the TC (for a 2 keV beam) is approximately 250 m, with the consequence that there are virtually never two fast H atoms in the TC at the same time. The pressure of the target gas in the TC was selected such that a sufficiently high signal count rate was received at the detector, while being kept low enough to limit secondary collisions from involving more than 9 – 10% of the stripped/attached product ions. These secondary collisions will be discussed in the 'corrections' section of this thesis.

Located immediately after the exit aperture of the target cell are two sets of deflection plates. After passing through these plates the fast H atoms and ions travel through a field-free region roughly 66 cm in length before striking the detectors. A small set of plates (DP2) defining a vertical electrostatic field is used to deflect the product ions away from the beam axis during the accumulation of background counts. A second set of plates (DP3) provide a horizontal electrostatic field that serves to deflect the product ions to a detector (PSD2). Due to the fact that the elastic scattering cross section for neutral hydrogen by the various target gases is much larger than those for stripping or attachment, it is necessary to deflect the product ions of interest far enough away from the
beam axis so that they can be distinguished from elastically scattered neutrals. Since the angular dependences of the stripping and attachment signals are to be measured, it is necessary to minimize the distortion of the product scattering pattern induced by deflection and the horizontally-deflecting plates were designed and operated with this in mind. Before construction, the plates were modeled on a computer which showed them to be capable of deflecting ions through an angle of seven degrees without introducing any observable distortion within 350 μm. The resulting design consists of plates that are long enough in the vertical direction to appear infinite to the beam, and 8.0 cm long in the direction parallel to the beam axis. This geometry provides a relatively flat, uniform field between the plates and minimizes the beam focussing effects associated with deflection. To further minimize distortion of the pattern of signal ions at the detector, bipolar voltages are applied to the plates during operation so that the region midway between the plates is at ground potential. This helps to minimize focussing of the ions as they enter the deflection plates. To test the operation of the plates, elastic scattering of He\(^+\) by a He target was measured with the scattered ions deflected off axis. Due to its pronounced structure as a function of angle, this cross section should readily show any distortion present. No asymmetry was observable in this measurement.

**Detector Design and Operation**

A position-sensitive detector (PSD) with a 25 mm diameter active area is placed on the beam axis at a distance of 74 cm from the TC exit aperture. This detector collects unscattered primary beam atoms as well as directly scattered neutral H atoms. A second PSD with a 40 mm diameter active area is placed off of the beam axis in the same plane as the on-axis detector and is used to collect the deflected product ions.

Each PSD consists of two micro-channel plates (MCP's) placed in front of a resistive anode. The MCP's, whose channels are tilted a few degrees from the normal,
are oriented in a chevron configuration to insure that particles impacting at normal incidence cannot travel straight through the channels without impacting one of the inner walls. Upon impacting a channel wall, a secondary electron may be ejected and, under the influence of a potential difference of approximately 1000 volts across the MCP, initiate a cascade of secondary electrons. Typically, this cascade results in approximately 1000 to 3000 electrons leaving the back face of the first MCP and entering channels in the second MCP. Accordingly, a burst of approximately $10^6$ to $10^7$ electrons leave the back face of the second MCP. These electrons are deposited on a resistive anode, where the charge distribution is decoded to give the initial particle's impact position (see ref. 9 for more details on the PSD design and operation). The front MCP is operated with a bias voltage of approximately -55 volts applied to its front surface which serves to repel both low energy electrons scattered from the chamber walls as well as electrons ejected by fast particles impacting the inter-channel surface of the MCP. The electrons ejected from the inter-channel surface would otherwise be capable of travelling some distance across the face of the MCP before possibly entering a channel, thus giving rise to erroneous position information.

The 40 mm PSD is positioned off the beam axis such that a particle deflected five degrees off axis immediately after the target cell will impact the detector near the center of the active area. Since the angle of the channels with respect to the detector surface normal on this detector is five degrees, care is taken to insure that the channels are tilted vertically, orthogonal to the direction of deflection. If the channels are oriented towards or away from the direction of deflection, the angle between the channel and the incoming particles could be as small as $0^\circ$ or as large as $11^\circ$, possibly leading to a large variation in detection efficiency across the detector face$^9$. This eliminates the need to tilt the detector face towards the incoming particles.
Care is also taken in the choice of bias voltages applied between the front and back faces of the detectors by the PSDs' voltage divider circuits. For a given particle flux density (particles per unit time per unit area) there is an optimum voltage bias that will give a maximum detection efficiency. If the voltage applied is too high or too low, the amount of charge deposited on the anode will be too large or too small, and the decoding electronics will discriminate against these events. This discrimination occurs because the decoding electronics has circuitry which will only accept and decode charge signals that lie within a charge 'window', since charge signals outside this window result in inaccurate position indications. During data taking the off-axis detector (PSD2) only sees the scattered product ions, which represent a low particle flux density. By deflecting an ion beam of appropriate energy and similar flux density onto the PSD and varying the bias voltage, an operating voltage for maximum detection efficiency is found.

When this test is performed with a high flux localized to a small area on the PSD, the voltage required for maximum detection efficiency increases. The reason for this higher optimum voltage is that there is a local depletion of electrons in the MCP in the region of the high flux. This results in fewer electrons being ejected from the microchannel walls of the second plate. The higher bias voltage increases the gain of the plates so that the amount of charge leaving the second plate is again in the charge 'window' that is accepted by the decoding electronics. During data taking the on-axis PSD (PSD1) is subjected to both a high flux density at the spot where the unscattered primary beam atoms are incident, and a low flux density elsewhere due to elastically scattered atoms. Since both of these signals represent primary beam atoms entering the target cell, it would be best if the detection efficiency for the two signals is equal. This is achieved by measuring the detection efficiency curve versus bias voltage for both high and low flux density conditions and then operating the PSD at the voltage corresponding to the intersection of the two efficiency curves. Before this intersection is taken, the maxima of the two curves
are normalized to one another. This procedure assumes that the maximum detection efficiency attained in the two cases is indeed the same. Further tests are performed to justify this assumption under the present operating conditions, details of which are given in the 'detector calibration' section of this thesis.

Another concern when using a PSD is the uniformity of the detection efficiency and the linearity of its position determination across its face. The linearity is tested by mounting a metal grid of 100 lines per inch immediately in front of the PSD and then rastering an ion beam across the face of the PSD. The shadow of the metal gridwork is clearly visible after several minutes of data accumulation and provides a known reference for physical length in both dimensions on the PSD. Non-linearities would clearly appear as differing distances between grid lines. This test also allows for calibration of computer memory bin sizes into real physical dimensions. Results of this test show that for nine bit resolution in the digitizing of position voltages from the 40 mm PSD, one computer bin corresponds to a 106 x 106 μm area on the PSD surface.

Uniformity tests consist of rastering an ion beam across the PSD face with a triangular waveform so that the beam spends an equal amount of time over each part of the PSD. A contour plot of the resulting accumulated data reveals any local peaks or dips in the efficiency which are larger than normal statistical fluctuations. Another similar test involves rastering the ion beam in a small square area, and then to move this area around to several different positions on the PSD, being careful that the beam spends an equal amount of time at each position. A count of the number of recorded events at each position compared to those at other positions then serves to reveal non-uniformities. Before taking data for this experiment, it was ascertained that the uniformity of the PSD's varied by less than two percent across their faces. Near the end of the experiment, another less rigorous uniformity test was performed to check that the condition of the
PSDs had not changed. The observed variation (above the standard deviation expected for the statistics accumulated) was only 2 to 3 percent.

**Cross Section Determination**

The attenuation of the primary beam in passing through the target cell is given by the expression

$$S_0 - S_f = S_0 \left( 1 - e^{-\tau \sigma} \right)$$

where \( \tau \) is the target thickness, \( \sigma \) is the cross section for the process of interest, \( S_0 \) is the flux of incident primary beam atoms and \( S_f \) is the flux of unscattered atoms left in the beam. Solving this for the total cross section \( \sigma \), assuming the product \( \tau \sigma \ll 1 \), yields

$$\sigma \approx \frac{S_m}{S_0 \tau}$$

where \( S_m \) is the flux of scattered particles measured, or \( S_m = S_0 - S_f \). The target thickness \( \tau \) can be expressed as the product \( nl \) where \( n \) is the number density of the gas target, and \( l \) is the length of the target cell. This simple expression for \( \tau \) results from the fact that gas leaving the target cell (TC) through the exit aperture increases the number density immediately outside the TC with a corresponding decrease inside the TC. This would suggest that the product \( nl \) is too simple an expression to accurately describe the target thickness seen by the ion beam. However, computer modelling and experiments done by other members of this group\textsuperscript{11} show that for a target cell of the dimensions used in this experiment the decrease in target density inside the TC is compensated for by the increase in target density outside the TC. Thus the product \( nl \) is an accurate representation of \( \tau \). Incorporating this into (5) and differentiating with respect to angle gives the expression used for differential cross sections:

$$\frac{d\sigma(\theta)}{d\Omega} \approx \frac{\Delta S_m(\theta)}{S_0 nl \Delta \Omega}$$

(6)
where now $\Delta S_m(\theta)$ is the flux scattered into the solid angle $\Delta \Omega$ at a scattering angle $\theta$. Using this equation, a measurement of all the quantities on the right hand side yields the differential cross section as a function of scattering angle $\theta$.

**Detector Calibration**

In calibrating the detectors there are four issues of concern. The first is that there are two different detectors used, where one detector monitors the primary beam and the other collects the product ions. In order to put the differential cross sections on an absolute scale the relative detection efficiency between the two PSD's must be measured. The second issue concerns the large difference in particle flux densities between primary and secondary particles, which affects the detection efficiencies. Thirdly the MCP's can deteriorate with use, and fourth the detection efficiencies for neutral particles and ions may differ. The first two issues are inter-related and will be discussed together.

Before the relative detection efficiency of the two PSD's can be measured, their optimum operating voltages must be found by the methods described earlier. Once the PSD bias voltages are set to these values, an ion beam of the same energy and similar intensity as the neutral beam to be used during the experiment is formed. By repeatedly deflecting this beam back and forth between the two PSD's and counting the number of events on each detector, a relative detection efficiency for the two detectors can be determined. But as stated earlier, beams of equal flux but different flux densities may result in different detection efficiencies, depending on the operating voltage chosen for the PSD. On PSD2, the calibrating beam must be rastered rapidly over a large area to give a low flux density, thus simulating the flux density the detector will see during data accumulation. Since the calibrating beam's intensity is matched to that of the experiment's primary neutral beam, the overall count rate on PSD2 is much higher during calibration than during data taking. However, tests have shown that the rastered beam's
intensity can be varied greatly without any noticeable shift in the optimum operating voltage, thus leaving the detection efficiency unchanged. (This is not true, however, for dramatic changes in the detector surface area covered by the beam, such as when changing between a 'point' beam and a rastered beam.) Thus the higher intensity ion beam rastered on PSD2 should accurately reflect the detection efficiency of the PSD under data taking conditions. On PSD1, the operating voltage has been chosen such that a point beam and a rastered beam should be detected with the same efficiency. Thus it should make no difference which flux density is used for calibration. To avoid unnecessary aging of the MCP (see below), the calibration of PSD1 is performed with a rastered beam.

The third issue of concern is a complication which arises from the fact that an intense point beam impacting the same spot on a PSD will, over time, reduce the detection efficiency at that spot due to aging of the MCP surface. This requires that the neutral beam be repositioned on the PSD frequently to prevent any one spot from losing a significant amount of efficiency. Unfortunately, this aging process puts into question the assumption made earlier that the maximum efficiencies attained for a point beam and for a rastered beam are equivalent. Consider that for an incoming particle to be detected as a valid event it must first eject a secondary electron from the front MCP, and then the resulting burst of electrons leaving the back of the second MCP must have a magnitude within given limits. Varying the operating voltage of the PSD affects the amount of charge leaving the second MCP, but has no effect on the probability that the incident particle will eject a secondary electron in the first place. It is believed that the aging phenomenon reduces this electron ejection probability, and so it is necessary to justify that the above assumption is not invalidated in this experiment. It should be pointed out that the rate of aging increases dramatically with increasing energy of the incident particles. Therefore the worst case under which to test the assumption would be after all
of the data for the highest energy projectile, in this case 5.0 keV, were accumulated. An ion beam with this same energy was formed and deflected to impact the MCP in the same place where the neutral beam hit during all of the 5.0 keV absolute data accumulation. By switching the ion beam back and forth between this spot and a rastered pattern over the MCP surface, and simultaneously switching the PSD bias voltage to maximize efficiency for a point and rastered beam, a count of valid events for the two cases was compiled. After several trials the largest deviation between the two efficiencies observed was less than 0.2%, which is considered acceptable. This test shows that by adjusting the PSD operating bias to give the maximum detection efficiency, one can ensure that the overall detection efficiency of the PSD remains constant.

The fourth issue which merits consideration is the difference in detection efficiencies for neutral particles and ions of the same species and energy. Tests performed by other members of this research group\textsuperscript{10} show a difference in efficiency as high as approximately 2.5% for neutral and ionic projectiles of 1.5 keV incident on the same PSD. Since the present experiment measures neutral atoms on one PSD and ions on another, a difference of 5% would be expected for particles of 1.5 keV. This is attributed to different secondary electron ejection coefficients for incident ions and atoms, and is not a completely repeatable value. For this reason an uncertainty is added to the measured cross sections. Further, these differences decrease with increasing projectile energies. At 5.0 keV it is expected that all differences vanish and detection efficiencies are equivalent. Thus the uncertainty in the integrated cross section measurements due to this phenomenon listed in table 1 varies with projectile energy.

**Measured Quantities**

The quantities recorded during data taking include the target cell gas pressure (in order to get the number density $n$) which is recorded with an MKS Instruments Baratron
capacitance manometer with an operational range of 1.0 to 1.0 x 10^-5 torr. Its output of 0.0 to 12.4 volts (corresponding to 0 to 0.124 torr) is digitized with 11 bits of resolution and stored on a Motorola 131 computer. Typical target cell gas pressures fall within 12 to 19 mtorr, and the pressure measurement takes place off of the beam axis far from the entrance and exit apertures of the TC. The length of the target cell is determined by measuring the distance of travel of a microscope lens focused through the cell first on the entrance aperture and then on the exit aperture. For this experiment the TC length was found to be 2.60 mm with an estimated uncertainty of 0.05 mm. The primary beam count rate and total number of counts are monitored using the output of PSD1 routed into a Surface Sciences Laboratories decoding electronics unit (EU1), whose output is sent to a Bira Model 2101 Scaler/Timer, where the number of valid events on PSD1 is recorded. Another decoding electronics unit (EU2) is used to decode the outputs from PSD2. The outputs from EU2 consist of two analog voltages representing x and y positions and a TTL strobe pulse indicating a valid event. The x and y voltages are digitized using nine bits of resolution, with the strobe pulse acting as a trigger for conversion. The digitized x and y coordinates are then converted to a location in a 360 x 360 bin computer memory array with each bin corresponding to a 106 x 106 μm square on the detector face. Each time a count is received, the content of the bin in which the count falls is incremented by one. Thus the computer accumulates a two-dimensional histogram that shows the pattern of particle impacts on the detector face. The two electronics units require different amounts of time from the moment of a particle impact until a strobe pulse indicating a valid event is output, with EU1 taking 16 μs, and EU2 taking 8 μs. Digitization of valid events from EU2 takes an additional 25 μs. Uncertainties associated with the various measured values are found in table 1.
Table 1. Experimental Uncertainties

<table>
<thead>
<tr>
<th>Experimental Quantity</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross Section Amplitude Uncertainties:</strong></td>
<td></td>
</tr>
<tr>
<td>Counting statistics</td>
<td>2 %</td>
</tr>
<tr>
<td>PSD operating point</td>
<td>2 %</td>
</tr>
<tr>
<td>PSD calibration</td>
<td>1 %</td>
</tr>
<tr>
<td>TC length l</td>
<td>2 %</td>
</tr>
<tr>
<td>Secondary collision correction</td>
<td>3 %</td>
</tr>
<tr>
<td>TC pressure (number density $n$)</td>
<td>1 %</td>
</tr>
<tr>
<td>Baratron thermal transpiration</td>
<td>2 %</td>
</tr>
<tr>
<td>Neutral/Ion detection efficiency, 2 keV</td>
<td>5 %</td>
</tr>
<tr>
<td>Neutral/Ion detection efficiency, 5 keV</td>
<td>0 %</td>
</tr>
<tr>
<td><strong>Cross Section Angular Uncertainties:</strong></td>
<td></td>
</tr>
<tr>
<td>TC to PSD distance</td>
<td>1 %</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>0.009°</td>
</tr>
<tr>
<td>Analysis ring width (106 μm)</td>
<td>0.008°</td>
</tr>
<tr>
<td>PSD position encoding error $1^5$</td>
<td>0.008°</td>
</tr>
</tbody>
</table>

Data Accumulation

Accumulation of data is performed in two stages. In the first stage, optimum operating voltages are determined for each PSD as described earlier, followed immediately by admission of the appropriate gases into the CTC and TC. Voltages are applied to the horizontally-deflecting plates after the TC (DP3) so that the H$^-$ product ions are incident on PSD2, the vertically-deflecting plates after the TC (DP2) are grounded, and accumulation of data begins. No calibration is performed between the two detectors, so the resulting measured cross sections are only relative. This disregard for an accurate accounting of the number of primary beam atoms entering the TC and the resulting
disregard for the aging of the PSD at the point of the primary beam impact allows for lengthy data accumulation times. Due to the small cross sections being measured, these long accumulation times are necessary in order for the number of product ions collected at the larger angles to be statistically meaningful. Once enough statistics are accumulated, the computer memory array is stored in a file on a hard disk. A typical raw data file containing the accumulated signal histogram is shown in figure 2. The deflection plates DP3 are then grounded, and voltages are applied to the plates DP2 in order to deflect the product ions away from the detectors. With this configuration another data file is accumulated with only background counts incident on PSD2. There are at least three sources for background counts. First there are 'dark counts' due to stray electromagnetic radiation, tunneling of electrons out of the MCP surface, etc. which are independent of the operating conditions of the apparatus. There are also counts due to stray beam particles which are scattered from chamber walls or from the edges of apertures, etc. and arrive at the PSD with enough energy to be detected. Thirdly, there are primary beam atoms which are elastically scattered by the target gas through a large enough angle to impact PSD2. Since these types of events must be subtracted from the data signal, it is necessary to accumulate a statistically accurate duplication of the occurrence of these events which took place during the data signal accumulation. For this reason, the time of accumulation, TC pressure, and primary beam count rate during 'background' data accumulation are matched to those of the 'signal' file as closely as possible. Typically the average TC pressures between the two files differ by less than 0.5% and the average primary beam count rates (and thus the total numbers of counts) differ by less than 0.2%. Corrections for these differences will be discussed later. Lastly the deflection plates DP2 are again grounded, voltages on the plates DP3 deflect the H\(^+\) product ions onto PSD2, and data are accumulated again. By matching the operating conditions for this stripping data file to the two previous files, it is possible to use the one background file for
Figure 2. Histogram of typical data accumulated on the PSD

subtraction from both signal files. This is done to avoid the need for two different background files for the two processes being measured, thus minimizing both the amount of time needed for data accumulation and aging of the PSD. Once this sequence is finished, another target gas or another projectile energy is chosen and the process is repeated.

In the second stage of data taking, the steps described above are again followed with two exceptions. First, the two PSD's are calibrated against one another after the appropriate PSD bias voltages are determined. This is performed as described earlier with a rastered ion beam. Once a value for the relative detection efficiencies is attained, data are accumulated using the same procedure as for the relative measurements. Second, the data are now taken quickly so that the measurements can be made before significant aging of the MCP occurs. This insures that the calibration performed remains valid over
the entire duration of data accumulation. Data is taken just long enough to get enough statistics to determine the integrated cross sections to within approximately 1.5%. Some of the smaller attachment cross sections have a slightly higher uncertainty, while the stripping cross sections generally are determined to within a smaller uncertainty.

During data taking several of the parameters can drift and require occasional corrections to keep them near their original value. The two most notable examples are the target cell pressure and the primary beam count rate. In the case of the TC pressure, the measured cross section must be corrected by a function that is not a linear function of pressure (see 'corrections' section). Thus it would not be proper to let the pressure vary greatly and then just take the average value to be used in determining the cross section. For this reason, care was taken to ensure that the pressure never varied by more than about 1.0% over the course of a data file accumulation. Similarly a correction must be made for the dead time of the counting electronics which is not a linear function of the primary beam count rate. Less stringent standards were kept on the minute-to-minute variation of the count rate, with typical variations on the order of 5 to 6%. The reason for this is that the dead time correction to the measured quantities itself is usually under 4%. In addition, it is nearly impossible with the present apparatus to maintain a stable beam within tighter limits.

Data Analysis

As stated earlier the position information from the PSD is stored in a 360 x 360 computer histogram. When analyzing this type of data it is first necessary to determine where the center of the scattering pattern lies. Two methods are employed in determining the center. The first method, or 'linear fit' method, involves selecting a square area centered on the computer bin containing the highest number of counts. Typical sizes for these squares range from 30 x 30 bins to 70 x 70 bins. Then for each row of bins
(x-direction) in the square the center of mass of the counts in that row is found and recorded. A linear fit is then made to this set of points representing the centers of mass of each row, with each point weighted by the number of counts in the row it represents. This same procedure is repeated for each column (y-direction) and another linear fit is made. The intersection of these two lines is then taken to be the center of the scattering signal. The second method, or 'center of mass' method is not much different. In this method, the x and y positions of the center of mass of all the counts in the square are found independently of one another and this coordinate is taken to be the center. Both methods are used on each data file, and with few exceptions the two methods agree on the position of the center to within 0.2 bins. Data files in which the statistics are poor or the cross section is relatively narrow-peeked present the few cases in which the two methods show significant disagreement. In such cases preference is given to the center of mass method since the accuracy of the linear fit method is questionable under these conditions.

After determination of the scattering center position, concentric rings about that position are defined and the counts in each ring are summed and stored in a one dimensional array. The width of the rings is increased for the larger-radius rings because of the rapidly diminishing number of counts at the larger scattering angles. The scattering angle corresponding to the average angle subtended by the ring is assigned to the data point associated with each ring. Also, as the rings get larger they begin to extend beyond the region of the PSD's active area. To correct for this, the fraction of ring area which lies outside of the active area is determined and the array elements holding the ring sums are scaled accordingly. (Actually the boundary defining the edge of the PSD data does not correspond with the edge of the PSD itself, but with a software mask that cuts off the edge of the PSD. This eliminates irregularities in linearity and detection efficiency uniformity normally present at the edges of the detector.) Using the same center position
from the data file on the background file an array of ring sums containing background counts is compiled in a like manner.

**Corrections to Data**

Before these two arrays can be subtracted they must undergo several corrections. The first corrects for secondary collisions inside the target cell. Once a product ion is formed it may undergo another collision with a target gas atom before exiting the TC. Secondary collisions resulting in the re-neutralization of the fast product ion will prevent the particle from being deflected onto PSD2 and being counted as part of the stripping/attachment signal. By using other investigators' cross section values for these processes\textsuperscript{12,13} an estimation of the number of particles lost is made, and the ring sums from the data file are corrected accordingly. In most cases this correction is kept below 9 – 10% by limiting the target cell gas pressure. Product ions can also undergo direct scattering collisions, resulting in a general shift of product ions from smaller to larger scattering angles. By measuring differential stripping cross sections for various TC gas pressures and observing this shift, an estimate of the maximum allowable pressure is made. The pressure is then kept below this limit such that no correction is necessary.

Another correction performed is a scaling of the ring sums to account for differences between the data and background files in the number of primary beam atoms entering the TC. This is typically a small correction on the order of a fraction of a percent. The primary beam count itself is corrected for several reasons. Some primary atoms are not detected due to the 16 $\mu$s dead time of the decoding electronics. The real number of primary beam atoms $T_R$ is calculated to second order using the equation

$$T_R \approx T_M [1 + \alpha + 2\alpha^2]$$

(7)

where $T_M$ is the total measured number of beam atoms, and $\alpha$ is the product of the average count rate times the dead time of the electronics. The primary beam count is also
corrected to reflect the relative detection efficiencies between the two detectors. This typically turns out to be a correction of about 2%. Also, in the target cell, some of the primary beam is scattered beyond of the acceptance angle of the 25 mm PSD used to detect that beam (PSD1). By using experimental data for neutral - neutral elastic scattering\textsuperscript{14,15} and deriving potential curves from these data, the cross sections for elastic scattering can be calculated out to 180°. This allows for an estimation of the percentage of primary beam atoms not collected on PSD1. The primary beam count is then adjusted upward accordingly, which in the worst case is on the order of a few percent. Lastly, the product ions collected on PSD2 are particles which started out as primary beam atoms, so the data array sum is added to the primary beam count. This last correction is as large as 3.5% for the largest cross sections, and as small as a few tenths of a percent for the smaller cross sections.

After all these adjustments are made, the differential cross section is calculated using eqn. (6). The error bars placed on the magnitude of each data point arise from the statistics of the counts in each ring, taking the square root of the sum of the squares of the standard deviations for the signal and background ring sums. The horizontal or angular error bars are calculated using the physical size of the beam on the PSD. Rather than use the maximum beam divergence calculated from the aperture geometry as listed in table 1., a data file is accumulated with a beam on the PSD and the calculated width of the distribution is used as the uncertainty in the angular position. This method accounts for both the beam divergence and the PSD position encoding error, which are the two largest angular uncertainties among those listed in table 1.
Results and Discussion

Absolute differential cross sections for \( H + X \) stripping and attachment have been measured for projectile energies of 2.0, 3.0, 4.0 and 5.0 keV and targets of He, Ar, \( \text{H}_2 \), \( \text{N}_2 \) and \( \text{O}_2 \) over a laboratory angular range of 0.02° to 1.77°. Differential data are presented in figures 4 through 12. As a consequence of the high angular resolution the data show definite structure below 1.0° in some of the cross sections, which have not been previously observed by other authors. Structure appears most notably for attachment in Ar and \( \text{H}_2 \) targets and stripping in He and \( \text{H}_2 \). In some collisions, such structure may be brought about by crossings of the potential energy curves for the initial and final states. Figure 3\(^1\) shows approximate potential curves for the \( H + \text{Ar} \) system. In the case of stripping the fast \( H \) atom, an electron is lost to the continuum. Thus the potential energy level for the \( H^+ + \text{Ar} \) final state is not really a discrete level but rather a continuum of levels. Although the scattering cross section for any one particular final state potential energy may show structure due to the curve crossing, the superimposition of all the possible final state energies washes out the structure in the observed signal. For attachment, however, there is not a continuum of \( H^- + \text{Ar}^+ \) potential energy levels, so the appearance of structure is not a surprise. This reasoning is consistent with the observed cross sections for argon. However, the appearance of structure in the \( H + \text{He} \) and \( H + \text{H}_2 \) stripping cross sections seems anomalous with this reasoning. Also surprising is the lack of any structure in the attachment cross sections for targets of \( \text{N}_2 \) and \( \text{O}_2 \). This may indicate that the \( H^- + X^+ (X=\text{N}_2, \text{O}_2) \) potential curves have crossings with those for excited states, and so the products may have several possible final states. Again the superposition of these cross sections would tend to wash out structure which may be present for each individual state.
Figure 3. Approximate potential-energy curves for the H + Ar system.

Comparisons of differential measurements with those of other authors are shown in figures 13 through 18. Stripping cross section comparisons with Fleischmann\textsuperscript{2} generally show good agreement at 5 keV. At 2 keV there is still good agreement between the slopes of the two measurements, although the present results tend to be higher than those of Fleischmann. It should be noted, however, that Fleischmann measured only relative cross section values which he normalized to agree with total cross sections of other authors. With this in mind, the differences between the absolute scales is not surprising considering the wide disagreement between various authors shown in table 2.
Figure 4. Differential cross sections for H + H₂ stripping. The data have been multiplied by the factors indicated.
Figure 5. Differential cross sections for H + N2 stripping. The data have been multiplied by the factors indicated.
Figure 6. Differential cross sections for H + O₂ stripping. The data have been multiplied by the factors indicated.
Figure 7. Differential cross sections for H + Ar stripping. The data have been multiplied by the factors indicated.
Figure 8. Differential cross sections for H + He stripping. The data have been multiplied by the factors indicated.
Figure 9. Differential cross sections for H + H₂ attachment. The data have been multiplied by the factors indicated.
Figure 10. Differential cross sections for H + N₂ attachment. The data have been multiplied by the factors indicated.
Figure 11. Differential cross sections for H + O₂ attachment. The data have been multiplied by the factors indicated.
Figure 12. Differential cross sections for H + Ar attachment. The data have been multiplied by the factors indicated.
Figure 13. Comparison of H + H₂ differential stripping cross sections. The data have been multiplied by the factors indicated.
Figure 14. Comparison of H + N$_2$ differential stripping cross sections. The data have been multiplied by the factors indicated.
Figure 15. Comparison of H + O₂ differential stripping cross sections. The data have been multiplied by the factors indicated.
Figure 16. Comparison of H + Ar differential stripping cross sections. The data have been multiplied by the factors indicated.
Figure 17. Comparison of H + He differential stripping cross sections. The data have been multiplied by the factors indicated.
Figure 18. Comparison of H + Ar differential attachment cross sections. The data have been multiplied by the factors indicated.
Comparisons with differential measurements of Cisneros\textsuperscript{4} and Martinez\textsuperscript{5} tend to be worse.

Present results for integrated cross section values are shown in tables 2 and 3 along with measurements performed by other investigators. Graphical comparisons between present measurements and other authors are presented in figures 19 through 27. Notice that in some cases not all of the data shown in tables 2 and 3 appear in the graphs due to the large number of measurements for some of the processes. Several different experimental methods were employed by the various authors, with wide disagreement in many cases both between their reported values and with the present results. Possible sources of error are recognized for a few of these measurements, but in many cases it is difficult to account for the discrepancies.

The values reported by Kudryavtsev and Sorokin\textsuperscript{28} are dramatically lower than the present results. Although they take steps to insure collection of product ions which are scattered through large angles by secondary elastic collisions, they do not mention any correction for loss of ions through secondary neutralizing collisions. Given the target thickness (nl) used in their experiment, this should be a substantial correction which would raise their total cross section values closer to the present results. This problem may also apply to the measurements of Curran and Donahue\textsuperscript{26}, which are also low, but there are too few details provided to say this with certainty.

Some discrepancies may be attributed to different detector acceptance angles. In the present apparatus, an acceptance angle of $1.77^\circ$ is used. A linear extrapolation of the data (on a log-log plot) to larger angles shows that as much as approximately 30\% of the total cross section may lie at larger angles. It is notable, then, that the higher results of Miethe \textit{et al.}\textsuperscript{25} may be attributable to their larger acceptance angle ($2.6^\circ$). Likewise, the
Table 2. Integrated differential cross sections for electron loss (stripping).

Present results are integrated over an angular range of 0.02° - 1.77°.
All cross sections are in Å².

<table>
<thead>
<tr>
<th>Process</th>
<th>This Work</th>
<th>Other Works</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(2 keV) + H₂</td>
<td>0.77</td>
<td>0.77ᵇ, 0.39ᵉ, 0.58ᶠ, 0.63ᵢ, 0.60ᵖ</td>
</tr>
<tr>
<td>H(3 keV) + H₂</td>
<td>0.97</td>
<td>0.95ᵇ, 0.52ᵉ, 0.90ᶠ, 0.90ᵢ, 0.79ᵖ</td>
</tr>
<tr>
<td>H(4 keV) + H₂</td>
<td>1.02</td>
<td>1.10ᵃ, 0.58ᵉ, 0.16ⁿ, 0.82ᵖ</td>
</tr>
<tr>
<td>H(5 keV) + H₂</td>
<td>0.95</td>
<td>1.16ᵃ, 0.62ᵉ, 0.92ᶠ, 0.44ᵍ, 0.43ⁿ, 0.79ᵖ</td>
</tr>
<tr>
<td>H(2 keV) + N₂</td>
<td>1.82</td>
<td>2.25ᶜ, 2.02ᶠ, 1.37ʰ, 1.65ᵏ, 2.0ᵐ, 0.94ᵈ</td>
</tr>
<tr>
<td>H(3 keV) + N₂</td>
<td>2.12</td>
<td>2.47ᶜ, 2.81ᶠ, 1.62ʰ, 2.3ᵐ</td>
</tr>
<tr>
<td>H(4 keV) + N₂</td>
<td>2.33</td>
<td>2.08ᵃ, 1.82ʰ, 2.8ᵐ</td>
</tr>
<tr>
<td>H(5 keV) + N₂</td>
<td>2.51</td>
<td>2.26ᵃ, 2.98ᶠ, 0.68ᵍ, 1.99ʰ, 3.0ᵐ</td>
</tr>
<tr>
<td>H(2 keV) + O₂</td>
<td>1.35</td>
<td>1.69ᶜ, 1.27ᶠ</td>
</tr>
<tr>
<td>H(3 keV) + O₂</td>
<td>1.78</td>
<td>2.11ᶜ, 2.22ᶠ</td>
</tr>
<tr>
<td>H(4 keV) + O₂</td>
<td>2.13</td>
<td>1.7₀ᵃ</td>
</tr>
<tr>
<td>H(5 keV) + O₂</td>
<td>2.33</td>
<td>1.92ᵃ, 2.90ᶠ, 0.7₁ᵍ</td>
</tr>
<tr>
<td>H(2 keV) + Ar</td>
<td>1.10</td>
<td>1.5₁ᵈ, 0.56ᵉ, 1.1₄ᵢ</td>
</tr>
<tr>
<td>H(3 keV) + Ar</td>
<td>1.13</td>
<td>1.3₄ᵈ, 0.8₅ᵉ, 1.1₀ᵢ</td>
</tr>
<tr>
<td>H(4 keV) + Ar</td>
<td>1.15</td>
<td>1.1₈ᵃ, 1.0₇ᵉ</td>
</tr>
<tr>
<td>H(5 keV) + Ar</td>
<td>1.2₇</td>
<td>1.3₃ᵃ, 1.₃₀ᵉ, 0.₈₁ᵍ</td>
</tr>
<tr>
<td>H(2 keV) + He</td>
<td>0.67</td>
<td>0.7₉ᵇ, 0.5₈ᵉ, 0.₇₈ᶠ, 0.₆₈ᵢ, 0.2₄ᵈ</td>
</tr>
<tr>
<td>H(3 keV) + He</td>
<td>0.₈₈</td>
<td>1.₀₀ᵇ, 0.₈₁ᵉ, 0.₉₉ᶠ, 1.₀₁ᵢ, 0.₃₇ᵈ</td>
</tr>
<tr>
<td>H(4 keV) + He</td>
<td>1.₁₀</td>
<td>1.₁₈ᵃ, 0.₉₇ᵉ</td>
</tr>
<tr>
<td>H(5 keV) + He</td>
<td>1.₁₂</td>
<td>1.₃₀ᵃ, 1.₄₈ᶠ, 0.₇₇ᵍ</td>
</tr>
</tbody>
</table>

Table 3. Integrated differential cross sections for electron capture (attachment).
Present results are integrated over an angular range of $0.02^\circ$ - $1.77^\circ$.
All cross sections are in $\text{Å}^2$.

<table>
<thead>
<tr>
<th>Process</th>
<th>This Work</th>
<th>Other Works</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(2 keV) + H₂</td>
<td>0.07</td>
<td>0.06\textsuperscript{b}, 0.03\textsuperscript{e}, 0.07\textsuperscript{i}, 0.04\textsuperscript{p}</td>
</tr>
<tr>
<td>H(3 keV) + H₂</td>
<td>0.13</td>
<td>0.12\textsuperscript{b}, 0.07\textsuperscript{e}, 0.15\textsuperscript{i}, 0.11\textsuperscript{p}</td>
</tr>
<tr>
<td>H(4 keV) + H₂</td>
<td>0.18</td>
<td>0.13\textsuperscript{e}, 0.14\textsuperscript{n}, 0.15\textsuperscript{p}</td>
</tr>
<tr>
<td>H(5 keV) + H₂</td>
<td>0.22</td>
<td>0.19\textsuperscript{e}, 0.13\textsuperscript{g}, 0.37\textsuperscript{n}, 0.18\textsuperscript{p}</td>
</tr>
<tr>
<td>H(2 keV) + N₂</td>
<td>0.08</td>
<td>0.04\textsuperscript{c}</td>
</tr>
<tr>
<td>H(3 keV) + N₂</td>
<td>0.10</td>
<td>0.07\textsuperscript{c}</td>
</tr>
<tr>
<td>H(4 keV) + N₂</td>
<td>0.11</td>
<td>--</td>
</tr>
<tr>
<td>H(5 keV) + N₂</td>
<td>0.20</td>
<td>0.11\textsuperscript{g}</td>
</tr>
<tr>
<td>H(2 keV) + O₂</td>
<td>0.19</td>
<td>0.16\textsuperscript{c}</td>
</tr>
<tr>
<td>H(3 keV) + O₂</td>
<td>0.24</td>
<td>0.19\textsuperscript{c}</td>
</tr>
<tr>
<td>H(4 keV) + O₂</td>
<td>0.24</td>
<td>--</td>
</tr>
<tr>
<td>H(5 keV) + O₂</td>
<td>0.24</td>
<td>0.12\textsuperscript{g}</td>
</tr>
<tr>
<td>H(2 keV) + Ar</td>
<td>0.15</td>
<td>0.11\textsuperscript{d}, 0.44\textsuperscript{e}, 0.16\textsuperscript{i}, 0.18\textsuperscript{r}</td>
</tr>
<tr>
<td>H(3 keV) + Ar</td>
<td>0.34</td>
<td>0.27\textsuperscript{d,r}, 0.40\textsuperscript{e}, 0.36\textsuperscript{i}</td>
</tr>
<tr>
<td>H(4 keV) + Ar</td>
<td>0.43</td>
<td>0.36\textsuperscript{e}, 0.38\textsuperscript{r}</td>
</tr>
<tr>
<td>H(5 keV) + Ar</td>
<td>0.42</td>
<td>0.34\textsuperscript{e}, 0.32\textsuperscript{g}</td>
</tr>
</tbody>
</table>

\textsuperscript{b}Van Zyl et al. (1980)\textsuperscript{18} \hspace{1cm} \textsuperscript{j}Roussel et al. (1977)\textsuperscript{24}
\textsuperscript{c}Van Zyl et al. (1978)\textsuperscript{3} \hspace{1cm} \textsuperscript{n}Curran and Donahue (1960)\textsuperscript{26}
\textsuperscript{d}Van Zyl et al. (1977)\textsuperscript{1} \hspace{1cm} \textsuperscript{p}McClure (1964)\textsuperscript{27}
\textsuperscript{e}Williams (1967)\textsuperscript{20} \hspace{1cm} \textsuperscript{r}Martinez et al. (1989)\textsuperscript{5}
\textsuperscript{f}Fogel et al. (1958)\textsuperscript{22}
Figure 19. Comparison of $\text{H} + \text{H}_2$ integrated stripping cross sections with other authors.
Figure 20. Comparison of H + N₂ integrated stripping cross sections with other authors.
Figure 21. Comparison of H + O₂ integrated stripping cross sections with other authors.
Figure 22. Comparison of H + Ar integrated stripping cross sections with other authors.
Figure 23. Comparison of H + He integrated stripping cross sections with other authors.
Figure 24. Comparison of $\text{H} + \text{H}_2$ integrated attachment cross sections with other authors.
Figure 25. Comparison of H + N₂ integrated attachment cross sections with other authors.
Figure 26. Comparison of H + O₂ integrated attachment cross sections with other authors.
Figure 27. Comparison of H + Ar integrated attachment cross sections with other authors.
$1.0^\circ$ acceptance angle used by McClure$^{27}$ may account for the lower values reported for both the stripping and attachment cross sections.

The values presented by McNeal and Clark$^{23}$ are the result of the subtraction of two numbers of comparable size. Thus, their values admittedly contain a large uncertainty, and a discrepancy with the present values is not too alarming. The stripping cross section results of Van Zyl et al.$^{1,3,18}$ are arrived at using the assumption that the angular distribution of the elastic scattering cross section for H atoms incident on the various target gases has the same shape as the differential stripping cross section, except for at very small angles. Elastic scattering measurements done in this lab$^{14,15}$ are plotted along with the present stripping and attachment data in figures 28 through 32 for 5.0 keV projectiles, and indicate that this assumption is valid and is not a source of error in the Van Zyl measurements.

Some authors who have noted the disturbing differences in cross section values have proposed the presence of unquenched metastable H(2s) states in the primary atomic beam as being responsible. In particular, both McClure$^{27}$ and Williams$^{20}$ have carried out experiments with metastable fractions in their atomic beams to investigate this possibility. Their findings indicate that while the expected rise in the cross sections is observed, it is too small a rise to account for the great differences between various reported values.

Aside from the possible sources of error discussed, the discrepancies in the data remain perplexing and unexplained by both the present author and many of the authors whose data are quoted. It should be noted, however, that uncertainties in the data referenced are in some cases as high as 20 – 30%, so although the actual data points are far apart, there is often agreement within the uncertainty of the measurements.

The values for both differential and total cross section measurements from other authors reported in this thesis were obtained mostly from graphical data. In only a few instances was tabulated data available. Although great care was taken to accurately
Figure 28. Comparison of H(5 keV) + H₂ stripping, attachment, and elastic scattering cross sections.
Figure 29. Comparison of H(5 keV) + N₂ stripping, attachment, and elastic scattering cross sections.
Figure 30. Comparison of H(5 keV) + O₂ stripping, attachment, and elastic scattering cross sections.
Figure 31. Comparison of H(5 keV) + Ar stripping, attachment, and elastic scattering cross sections.
Figure 32. Comparison of H(5 keV) + He stripping and elastic scattering cross sections.
retrieve numerical data from these graphs, some degree of inaccuracy is inevitable. Still, with a few exceptions\textsuperscript{4,22,28} it is believed that the original values are reported here with at most only a few percent inaccuracy.

Comparison of the present measurements with theoretical predictions would be both interesting and informative. Unfortunately there is little theory available. This is not surprising in the case of stripping since this is a three-body problem and as such is very difficult to model. Even so, some calculations have been done using the Born approximation\textsuperscript{16,19}, but the results don't agree well with experiment below about 100 keV. Similarly, somewhat reasonable agreement with experiment is shown for the classical impulse approximation at higher energies\textsuperscript{29}, but a treatment at lower energies is not performed. Theory for attachment is equally hard to find, perhaps due to difficulty in determining the potential curve for the H\textsuperscript{−} + X\textsuperscript{+} state, or for other states (such as excited states) which also must be considered.

Possible future work related to the experiment discussed here includes measurements of stripping and attachment cross sections for fast neutral atomic oxygen projectiles incident on H\textsubscript{2}, N\textsubscript{2}, O\textsubscript{2}, Ar and He. Combined with the atomic hydrogen projectile data, these measurements would represent a rather comprehensive set of data useful in modelling many of the processes which take place in the upper atmosphere.
References


10C. L. Hakes, Private Communication (1989)


15L. K. Johnson, Absolute Differential Cross Sections for Small-Angle Neutral-Neutral
(1987)


81, No. 13, 2231 (1976)


(1982)


27G. W. McClure, Phys. Rev., 134, No. 5A, A1226 (1964)

(1977)

(1969)