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Measurement of Electron-Loss Cross Sections
for 0.25 - 5 keV Hydrogen Atoms in Atmospheric Gases

by

Ken A. Smith

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

DOCTOR OF PHILOSOPHY

Thesis Director's Signature:

A handwritten signature in black ink, appearing to read "Theodore A. M. Smith", is written over a horizontal line.

Houston, Texas

September 1975

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I

Background

This thesis reports a measurement of electron loss cross sections for 0.25 to 5 keV hydrogen atoms in He, H₂, N₂, O₂, CO, CO₂, and CH₄. Electron loss or stripping processes in this energy range are currently of interest in both aeronomy and controlled thermonuclear reaction physics.

The aeronomic applications of hydrogen-atom stripping stem from the interaction between planetary atmospheres and the continuous flux of plasma that streams outward from the sun with a velocity of approximately 4×10^7 cm/sec. The ionic composition of the so-called "solar wind" flux is 96% H⁺, 4% He⁺⁺, and trace amounts of other elements. As the solar wind plasma approaches the earth, it interacts with the earth's magnetic field. As a result of this interaction, most of the solar wind ions are deflected around the earth and never enter the earth's atmosphere. Some of these particles, however, are trapped in the geomagnetic field and ultimately precipitate into the atmosphere, causing proton or hydrogen aurorae. A representative proton flux spectrum appears in Fig. 1 showing that most of the flux and a significant fraction of the total energy deposited in the atmosphere by the flux arises from

Figure 1. Auroral proton energy spectrum and energy distribution.

particles of energy less than 5 keV. The precipitating protons approach the atmosphere following helical paths with axes parallel to the geomagnetic field as shown in Fig. 2. The diameter of the helix depends on the proton's energy and the helix pitch, but a typical helix diameter for a 1 keV proton is ~ 50 m. As the proton travels down into the atmosphere it undergoes charge transfer with an atmospheric atom or molecule, converting the proton into a fast neutral hydrogen atom. The atom, unaffected by the earth's magnetic field, travels a rectilinear path until it loses its electron in a stripping collision, whereupon it again begins to spiral about the local magnetic field. The charge-transfer/stripping cycle repeats until the incident particle has given up almost all of its kinetic energy in collisions with atmospheric gases. If viewed from above, the path of the proton would resemble a random walk with successively shorter steps as shown in the Fig. 2 inset. The "random walk" terminates when the particle descends into atmosphere so dense that the distance traveled between successive stripping collisions is on the order of the particle's cyclotron radius. Under these conditions the particle's path is a helix with radius corresponding to the cyclotron radius of a particle having charge equal to e/m , where e is the electron charge and m is the ratio of the

Figure 2. Path of auroral proton.

stripping cross section to the charge-transfer cross section (Eather, 1967). Johnstone (1972) has shown that the mean horizontal distance $\underline{d}$ the particle travels in its "random walk" phase is on the order of $H(\frac{m}{m-1}) \ln m$, where H is the scale height of the atmosphere. Typically $\underline{d}$ is on the order of 200 km for a 3000 ev proton. Knowledge of this quantity is essential to understanding spatial structure of proton aurorae since the majority of the optical emission caused by an incident proton will come from regions that are removed by a distance on the order of $\underline{d}$ from the initial trajectory.

Since Venus has virtually no magnetic field, the solar wind interacts quite directly with the Venusian upper atmosphere, as shown in Fig. 3. While most of the solar wind plasma flows around the ionopause, the atmosphere is sufficiently dense at the ionopause that charge-transfer processes may neutralize some of the solar wind protons, allowing them to escape from the flowing plasma into the atmosphere below. This constant injection of fast hydrogen and helium atoms into the Venusian atmosphere may constitute a mechanism for local ionospheric heating and is likely to represent the principal source of hydrogen in the Venusian atmosphere (Butler, 1975).

Another important area of application of stripping

Figure 3. Interaction of the solar wind with the Venusian atmosphere.

processes lies in the field of plasma diagnostics. In controlled thermonuclear fusion studies, the plasma is typically confined by an intense magnetic field that serves to concentrate the plasma near the center of the reaction vessel. Since plasma contact with the walls causes the plasma to lose energy and, in fact, also results in rapid ablation of wall material, the magnetic field and reaction vessel are carefully designed so that a minimum number of charged particles escape the confinement region. In assessing the performance of the plasma machine, it is essential to know the plasma density, the electron temperature, and the ion temperature, since the value of these quantities reveal how closely the plasma ignition point is being approached. Typically the electron density is measured by Compton scattering of laser beams directed through various sections of the plasma, and the electron temperature is monitored by microwave interferometry (Gérard, 1975). In measuring the plasma ion temperature one would like to measure the energy spectrum of ions emerging from the plasma; but the confinement fields render such a measurement impossible. Neutral particles created by charge transfer inside the plasma, however, can freely cross the confinement field; and since there is very little momentum change involved in the charge-transfer process, the energy spectrum

of the fast neutrals emerging from the plasma can give information about the ion temperature of the plasma, provided that one knows the relevant charge-transfer and stripping cross sections and the plasma density profile. One can determine the energy spectrum of the atoms emerging from the plasma by converting the atoms to ions by stripping in a gas cell and using standard energy analysis techniques to determine the ion energy spectrum (Eubank and Wilkerson, 1963). Some correction of the measured spectrum for energy loss in the stripping process is necessary; but typical neutral energies lie between 100 eV and 40,000 eV, and the stripping energy loss is on the order of 10 eV (Fleischmann and Tuckfield, 1968). Obviously one must know at least the form of the stripping cross section as a function of energy in order to determine the temperature of the neutral flux entering the stripping cell; and if the flux of neutrals is to be determined, one must know the absolute stripping cross sections as well.

Both applications of stripping mentioned above concern stripping of hydrogen or deuterium atoms in the energy range between 100 and 40,000 eV in multi-electron-atom targets - typically atomic oxygen, helium, and molecular nitrogen in the aurora problem, and usually N_2 or argon in the CTR application. A search of the literature reveals

that there is no adequate theory for prediction of absolute stripping cross sections for light atoms of energy less than 10 keV. The literature contains some physically-motivated, empirical scaling relations that predict cross sections for light-atom stripping at low energies, usually within a factor of three (Fleischmann et al., 1972; McNeal and Green, 1970). Presently accurate stripping cross sections for light projectiles at low energies can only be obtained by direct measurement.

II

Techniques used in Measurements of
Stripping Cross Sections

Techniques for measurement of stripping cross sections at low energies fall into three general categories. Historically, the first technique used was a measurement of the attenuation of a fast neutral beam in a gas cell containing an electric field that removed all charged particles from the beam after their formation in stripping or electron-capture collisions. An alternative approach to stripping cross section determination is measurement of all the ion and electron currents produced in a gas cell as a fast neutral beam passes through the cell. A third method is used in the present experiment, in which the current of fast protons produced in electron-loss collisions of fast hydrogen atoms in a gas cell is measured directly. The advantages and disadvantages of these techniques are discussed in this chapter.

The attenuation technique

In 1956 Stier and Barnett published a comprehensive paper dealing with charge-changing collisions of protons, hydrogen atoms, and negative hydrogen ions in the energy

range of 3 keV to 200 keV. A number of different techniques were used, but here only that portion of the experiment relevant to low energy stripping of hydrogen atoms will be discussed. Stier and Barnett's apparatus is shown in Fig. 4. A beam of fast hydrogen atoms formed by charge transfer passed into a gas cell containing a pair of electrostatic deflection plates. As protons and H^- ions were formed in the cell, the field between the plates deflected them from the beam. The intensity of the neutral beam emerging from the cell is given by

$$I = I_0 e^{-n(\sigma_{0,1} + \sigma_{0,-1})l} \quad (1)$$

where I_0 is the initial beam intensity, n is the gas density in the cell, and l is the cell length. The sum of the cross sections for stripping and electron capture is then given by the slope of a plot of $\ln(I/I_0)$ versus nl . The main advantages of this attenuation technique are its mechanical simplicity and the fact that the absolute efficiency of the detector used for the neutral flux need not be known, since the quantity measured is the ratio of the neutral flux passing through the gas-filled cell to the total neutral beam flux.

A principal source of experimental uncertainty results from angular scattering of the stripped protons. At

Figure 4. Stier and Barnett's apparatus (illustrating attenuation theory).

sufficiently low energies some fraction α of the stripped protons will strike the exit slit of the cell and fail to reach the detector. One can evaluate the fraction α if the apparatus geometry and the differential cross section for stripping are known. The experimental procedure used by Stier and Barnett consisted essentially of observing the change in the neutral flux in a charge-equilibrated beam when the electric field inside the stripping cell was turned on. To make the effect of angular scattering more apparent, one can write

$$\sigma_{0,1} = \alpha \sigma_{0,1} + (1 - \alpha) \sigma_{0,1} ; \quad (2)$$

likewise

$$\sigma_{0,-1} = \beta \sigma_{0,-1} + (1 - \beta) \sigma_{0,-1} \quad (3)$$

where β is the fraction of negative ions missing the detector due to angular scattering in the charge-transfer process,

In the following, $\sigma_{0,-1}$ will be neglected, since Stier and Barnett showed that $\sigma_{0,-1}$ is more than one order of magnitude smaller than $\sigma_{0,1}$. With the cell field off, Stier and Barnett measured the intensity of the neutral flux I emerging from the cell, given approximately by

$$I = I_0 e^{-(\sigma_s + \alpha \sigma_{0,1}) n l} , \quad (5)$$

where I_0 is the neutral flux in the beam entering the cell, and σ_s is the cross section for scattering of neutral particles by an angle large enough to miss the detector. With the cell field on, they measure the neutral flux I' emerging from the cell, given approximately by

$$I' = I_0 e^{-(\sigma_s + \sigma_{0,1}) n l} . \quad (6)$$

Stier and Barnett apparently determined the "stripping" cross section from the relations

$$\begin{aligned} \ln \frac{I'}{I_0} &= -(\sigma_s + \text{"}\sigma_{0,1}\text{"}) n l \\ \ln \frac{I}{I_0} &= -\sigma_s n l \end{aligned}$$

giving

$$\text{"}\sigma_{0,1}\text{"} = \frac{1}{n l} \left(\ln \frac{I}{I_0} - \ln \frac{I'}{I_0} \right) . \quad (7)$$

If one takes account of angular scattering in the stripping process, the equations must be rewritten:

$$\ln \frac{I'}{I_0} = -(\sigma_s + \sigma_{0,1}) n l \quad (8)$$

$$\ln \frac{I}{I_0} = -(\sigma_s + \alpha \sigma_{0,1}) n l . \quad (9)$$

Obviously

$$\text{"}\sigma_{0,1}\text{"} = \sigma_{0,1} (1 - \alpha) , \quad (10)$$

and if $\alpha \ll 1$, the experiment yields an accurate value for $\sigma_{0,1}$; however, based on the differential cross sections for stripping recently measured by Fleischmann et al. (1974) and on the apparent cell geometry at the lowest beam energies used in Stier and Barnett's experiment, α may have been as large as 0.3, resulting in reported stripping cross sections that are too low.

Charge-collection experiments

McNeal et al. (1970) used another means of determining stripping cross sections. Their apparatus appears in Fig. 5. The technique involves measurement of the number of charged particles produced by the interaction of a fast atom beam with the gas contained in the ionization chamber. A fast hydrogen atom beam entering the cell interacts with the target gas, producing free electrons and ions primarily through stripping and target ionization.

Figure 5. Typical total charge collection apparatus.

By choosing suitable bias voltages for the grid and back plate, McNeal et al. could cause either the electrons or the positive ions to strike the collector assembly. Therefore, the cross sections they measured were the cross sections for positive ion production σ_+ and for negative charge production σ_- . Assuming that processes (a) and (b) were the only sources of the collected charged particles, McNeal et al. computed stripping cross sections according to

$$\sigma_{0,1} = \sigma_- - \sigma_+ . \tag{12}$$

Of course, processes (a) and (b) are not the only processes which could produce charged particles in the ionization chamber; a list of additional processes includes Eq. 11(c) - (i).

One expects the cross sections for all of these processes to be significantly smaller than those for stripping and target ionization; and some of the cross sections for processes (c) - (i) have been measured recently by coincidence techniques and have been found to be relatively

small for the target gases studied (Afrosimov et al., 1972 and 1973). Unless sophisticated experimental techniques (such as coincidence measurements and/or mass spectrometry of the slow ions produced) are employed, one cannot conclusively identify the processes responsible for production of ions and electrons in charge-collection experiments.

A further difficulty arises in charge-collection experiments at low energies, where some of the primary beam particles scattered by the target gas strike various electrodes in the ionization chamber. These scattered particles and the secondary electrons resulting from their impact on ionization chamber surfaces may cause significant errors in the interpretation of the measured collector current in both the electron collection and ion collection modes. Currents arising from secondary electron ejection by ultraviolet photons produced in the cell may also yield erroneous results.

Direct measurements of stripping

The third commonly-used technique of measuring stripping cross sections involves measurement of the current of fast protons produced as a fast hydrogen-atom beam passes through a gas cell. The experiment described in this thesis falls into this "direct measurement" category; and similar

experiments have been carried out for 3 - 100 keV H-atoms by McClure (1964 and 1968). Since McClure's experiment differs in several ways from the present experiment, a brief description of his experiment follows.

Figure 6 illustrates McClure's apparatus. A fast neutral hydrogen atom formed by charge transfer in a gas cell T_1 passed directly into a stripping cell T_2 . The fast protons produced in T_2 were detected in a gas-filled proportional counter A. The proportional counter window spanned a narrow slit 0.0025 cm wide by 2.45 cm high. McClure measured the product current by deflecting the proton flux away from the beam axis with plates D_2 and by integrating the proton current while sweeping the detector slit S_5 across the proton beam. The flux of neutral atoms passing through the stripping cell was also determined by sweeping the detector slit across the neutral beam at a fixed rate and counting the output pulses from the proportional counter. This novel technique obviates calibration of the neutral beam detector in a subsidiary experiment.

McClure extensively investigated possible effects of highly excited hydrogen atoms present in his neutral beam. He first separated cells T_1 and T_2 so that hydrogen atoms of principal quantum number $n < 9$ had sufficient time to decay radiatively before reaching the stripping cell. He

Figure 6. McClure's apparatus (employing direct-measurement technique).

then subjected the neutral beam to a strong ($\sim 10^5$ volts/cm) electric field between T_1 and T_2 . The field strength was sufficient to field-ionize any hydrogen atoms of $n \geq 9$. Within his experimental errors McClure found that the highly-excited hydrogen atoms did not contribute to his measured cross sections.

III

Present Experiment

The original motivation for the present experiment came from the fact that stripping of low-energy hydrogen atoms constitutes a major source of background in the merging beam apparatus described in Smith (1973). In searching the literature on the subject it became apparent that there were no published direct measurements of stripping cross sections below 1 keV hydrogen-atom energy and very few measurements below 5 keV, even though the energy range below 5 keV is perhaps more important than any other energy region in the aeronomical and CTR-related applications discussed in Chapter I. The experiment was therefore designed to accomplish direct measurement of stripping cross sections at energies lower than those previously studied.

Since the main interest lay in processes in which a fast hydrogen atom is converted into a proton, namely

and since a measurement of the fast proton flux produced by collisions of a hydrogen-atom beam with a static target gas yields the sum of the cross sections for these processes, a "direct measurement" technique similar to that of McClure (1968) was chosen.

In the "direct measurement" technique a fast hydrogen-atom beam traverses a cell filled with the target gas, and the current of fast protons formed in stripping collisions within the cell is measured. The cross section is determined under "thin target conditions" by the relation

$$\sigma_{0,1} = \frac{I_P}{I_0 \underline{n} \underline{l}} \quad (14)$$

where $\sigma_{0,1}$ is the stripping cross section, I_P is the current of stripped protons, I_0 is the neutral beam flux, $\underline{n}$ is the target gas density, $\underline{l}$ is the target length, and "thin target conditions" are taken to mean that $I_P/I_0 \ll 1$. In the particular apparatus arrangement chosen for the present experiment, each of the quantities on the right of Eq. 14 was measured independently, and the considerations relevant to each of these measurements are outlined below.

In measuring the product proton flux one must be careful to ensure that essentially all of the product protons are collected. The question of complete product collection becomes particularly critical at low incident beam energies,

since at low energies many of the product protons are scattered through significant angles with respect to the incident beam axis. Both the proton detector and the cell exit aperture must therefore subtend a relatively large solid angle when viewed from the stripping cell.

Measurement of the neutral beam flux is accomplished by allowing the neutral beam to strike a metal surface and monitoring the current of secondary electrons ejected from the surface by the fast hydrogen atoms. Use of this method for absolute determination of the neutral flux requires that the secondary electron ejection coefficient γ^0 (defined as the average number of electrons ejected per incident neutral atom) be known for the detector surface for hydrogen atoms of all energies used. The secondary electron ejection coefficient depends somewhat on the particular surface used and on its level of contamination; hence, a subsidiary experiment measuring secondary electron ejection coefficients must be performed in the course of the stripping cross section measurement.

The target length $\underline{l}$ does not necessarily correspond to the geometric cell length. This lack of correspondence may arise from non-uniform pressure distributions around the cell entrance and exit orifices. As will be shown in the following chapter, use of a variable-length gas cell can

in principle eliminate such end effects from consideration in computation of the measured cross section.

The target gas density $\underline{n}$ is established by measuring the gas pressure in the stripping cell. The response of the pressure sensor should not depend on the kind of target gas used, and effects of pressure gradients in the gas cell due either to gas flow within the cell or thermal transpiration between the cell and the pressure measuring device must be accounted for.

In summary, the measurement of the stripping cross section consists of the determination of four quantities: I_p , I_0 , $\underline{n}$, and $\underline{l}$. The details of the measurements of these parameters are set forth in the following chapter.

IV

Apparatus and TechniquesBeam preparation

Hydrogen atomic and molecular ions generated in a low-voltage hydrogen-fed arc ion source were accelerated to the desired collision energy and focused by a three-element electrostatic lens, as shown in Fig. 7. A pure, mono-energetic proton beam was selected by momentum analysis in a confocal pair of 15 cm bending radius 60° sector magnets. The magnet system, which is detailed in Smith (1973), will transmit only particles having momenta within 0.14% of the momentum to which the magnets are tuned; therefore, the magnets restrict the energy spread of the transmitted H^+ beam to about 0.5% of the H^+ beam energy. The H^+ beam energy is approximately 5 to 10 eV greater than the source anode potential and, since extremely accurate knowledge of the projectile energy is not required for the present experiment, the ion beam energy was taken to be equal to the ion source anode potential.

The H^+ beam emerging from the magnets passes into a gas cell, where about 30% of the ion beam particles are converted into fast hydrogen atoms by charge transfer. Again, the details of fast neutral beam production are

Figure 7. Present hydrogen atom stripping apparatus.

discussed by Smith (1973). A major difficulty encountered in this method of neutral beam production is the possibility that some of the neutral atoms are formed in excited states. For the case of hydrogen atoms the problem of excited state formation has been extensively investigated, and the lifetimes of all relevant excited states are known. In the present experiment two types of excited states have lifetimes long enough that they may reach the stripping cell in appreciable numbers. These states are 2S states and Rydberg states of $n \geq 9$. The ion deflection field (typically 600 volts/cm) following the charge-transfer cell readily Stark-mixes the 2S state with the adjacent 2P state, which rapidly decays to the ground state by emission of Lyman- α photons. The Rydberg states remain in the beam, but they constitute a very small fraction (typically $\sim 0.02\%$ of the total beam flux) (Kingdon et al., 1970). Since the fraction of highly excited atoms in the H^0 beam is so small, the measured stripping cross section should be unaffected by their presence unless the stripping cross section for highly excited atoms is on the order of $500 \text{ \AA}^2$. A small beam component with such a large cross section should be revealed by the steep slope of a plot of signal versus target thickness at target thicknesses below 2×10^{13} particles per cm^2 , changing to a smaller slope as

the stripping cell becomes a thick target for the excited component of the beam. No such decreases in slope of plots of signal versus stripping cell pressure were observed. As noted in Chapter II, in a study of stripping of hydrogen atoms in hydrogen and H_2 , McClure (1968) systematically investigated the possible effects of the presence of highly-excited atoms in a fast beam of hydrogen atoms formed by charge transfer. Within experimental error McClure observed no change in measured stripping cross sections when all of the excited atoms were removed from his hydrogen-atom beam by field ionization. McClure's experiments were carried out at 63 and 100 keV, where production of highly-excited hydrogen atoms by charge transfer is expected to be significantly more efficient than it is in the 0.25 to 5 keV energy range of the present experiment. On the basis of McClure's measurements and the test outlined above, the measured cross sections reported here are taken to be representative of collisions of ground state hydrogen atoms with the target gases.

Stripping cell and proton collector

As outlined in Chapter III the design requirements for the stripping cell were that the cell be of variable length and that the proton collector subtend the largest solid

angle possible so that scattered protons could be efficiently collected. Continuous monitoring of the neutral beam flux further demanded that the product protons be deflected out of the neutral beam into a Faraday cup, allowing the neutral beam to pass into a separate detector. As shown in Fig. 8 the variable length requirement was met by mounting the cell entrance aperture on a reentrant tube that was threaded into the cell's front wall. By rotating the tube the cell length was easily altered. Signal measurements were executed at cell lengths of 2.5, 3.75, 5, and 6.25 cm; and the cross sections were determined from the slopes of plots of signal versus cell length.

The proton collector was a three-element Faraday cup placed approximately 5 cm from the cell exit. To ensure that the Faraday cup subtended the largest possible solid angle, all three elements were usually connected in parallel; and secondary electron suppression was obtained by biasing both deflector plates at potentials negative with respect to the Faraday cup. The cup mount was rotatable about an axis perpendicular to the plane of Fig. 8 centered at point K. The detail of the product-collection geometry shown in Fig. 9 reveals that for a 2.5 cm cell length all product protons scattered through angles less than 15° were collected, with particles scattered less than 7° being collected

Figure 8. Stripping cell.

DEFLECTION
PLATES

5.0

FRONT VIEW OF
FARADAY CUP

TOP VIEW, CELL AND CUP ASSEMBLY

Figure 9. Product collection geometry. Cup is shown rotated so that cup axis is parallel to neutral beam axis.

in the central part of the Faraday cup. When the Faraday cup is in the position shown in Fig. 8 it is expected that particles scattered by slightly more than 7° are collected by the central portion of the cup because of the focusing action of the deflection plates; and particles scattered by slightly more than 15° may be collected on the cup assembly due to the lensing effect of the deflection plate field penetrating the cell exit aperture. By measuring the current to the front element of the Faraday cup alone, with the cup in the position shown in Fig. 8, it was verified that a negligible amount of the product was scattered through angles sufficient to cause it to be collected on the front element. The results of this test are shown in Fig. 10. This result is particularly important, since it shows that even at the lowest beam energy the product collection efficiency was greater than 90% for scattering angles of less than about 7° ; and, since the angle subtended by the complete Faraday cup assembly was always between 7 and 15 degrees, essentially all the product was collected at all cell lengths used. A plot of signal versus cell length for a hydrogen atom beam energy of 250 eV is shown in Fig. 11. The measured signal appears to show a good linearity with cell length, indicating further that little product was lost due to angular scattering. The result is

Figure 10. Test for complete collection of product.

Figure 11. Strip proton signal versus cell length.

consistent with the measurement of current to the front element of the proton collector shown in Fig. 10.

The pressure inhomogeneity near the cell orifices may keep the target length $\underline{l}$ from being identical to the geometric cell length. As shown in Appendix I, one can argue that for an ideal cell there is no end correction, since the density depletion on the high-pressure side of the exit orifice is exactly cancelled by a corresponding density enhancement on the low-pressure side of the orifice. The cell geometry is, however, not ideal, and a much more sophisticated calculation of the density distribution in the vicinity of the orifice is required before a definitive statement can be made regarding the effects of density inhomogeneities.

Since exact a priori determination of the end effect is quite difficult, the empirical correction technique of varying the cell length was chosen. This method of correction for end effects has several additional advantages that make it a desirable technique, even if exact gas-kinetic density corrections have been calculated. These advantages are that (1) measurement of the cross section at several different cell lengths provides an essential consistency check on the values of the cross sections measured, (2) the linearity of the signal versus cell length

plots represents a further test of the possible loss of signal due to angular scattering, and (3) the variable length technique corrects for the effects of any spurious collision processes occurring outside the cell, as outlined below.

During the early stages of the present experiment it was discovered that for some target gases, a negative current appeared at the signal Faraday cup when the signal was not being deflected into the cup. A typical plot of Faraday cup signal as a function of deflection plate voltage is shown in Fig. 12, where the negative signal is clearly evident at low upper plate potential. This negative signal was a slowly varying function of deflection plate potential and was somewhat smaller when the lower plate was biased at - 20 V, instead of the - 300 V used during acquisition of the data shown in Fig. 12. The magnitude of the negative signal was proportional to the pressure in the gas cell. Among other things the negative signal may have been due to the formation of slow positive ions and/or electrons in collisions of the primary H^0 beam with the target gas streaming from the stripping cell orifice. The field of the deflection plates could cause some of the electrons to strike the Faraday cup. Also, slow ions formed in the field of the deflection plates can be accelerated

Figure 12. Stripped proton signal versus deflection plate voltage. Cell length is 2.5 cm. 38

toward the more negative deflection plate, and secondary electrons formed by the impact of these ions on the plate can reach the detector. Likewise, some negative detector current may arise from secondary electrons liberated at the plates by hydrogen atoms elastically scattered from the primary beam. The spurious current in the proton cup due to all of the above sources is expected to be proportional to the cell pressure, but should be independent of the cell length; therefore, computation of the cross section from the slope of a plot of signal per unit cell pressure versus cell length should yield cross section values that are unaffected by spurious currents generated in the region of the deflection plates.

Density measurement

The target gas density n is determined by measuring the cell pressure and relating the measured pressure to the cell density by the ideal gas equation. A comprehensive review of the vast literature concerning devices and techniques for pressure measurement is given by Redhead (1968). The most common technique for pressure measurement in collision experiments has been the use of the Bayert-Alpert ionization gauge. The ionization gauge determines the pressure by measuring the ion current produced by a known flux of

electrons passing through the gas contained in the gauge. Consequently, the sensitivity of the gauge for a specific gas depends on the geometry of the gauge and the electron-impact ionization cross section for the gas, therefore the gauge must be calibrated against an absolute manometer (such as a McLeod gauge) for each gas used. Recently diaphragm-type absolute manometers have come into widespread use. Typically these manometers measure pressure by sensing the deflection of a thin metal membrane interposed between a chamber held at a reference vacuum and a chamber maintained at the pressure to be measured.

In the present experiment a commercially-available diaphragm manometer (MKS Instruments 145AHS-1) was used. This manometer incorporates a titanium diaphragm as the center electrode in a differential capacitor and is sensitive to diaphragm deflection of as little as $0.25 \text{ \AA}$. Consequently the device can be used to measure pressures as low as 5×10^{-6} torr (Loriot and Moran, 1975). Since the instrument responds to such miniscule diaphragm deflections, dimensional stability of the sensing head is of extreme importance. Therefore, the head is temperature regulated at $49 \pm 0.14 \text{ }^{\circ}\text{C}$. Since the cell is operated at room temperature and connected to the head via a 0.3 cm ID tube, a small ($\sim 4\%$) correction must be applied to the

measured pressures to account for the effect of thermal transpiration between the cell and the sensing head. The transpiration effect is discussed in Dushman (1949), and the magnitude of the required correction has been experimentally verified by Loriot and Moran (1975) for a capacitance manometer of the type used in the present experiment.

A further source of uncertainty in determining the target density is the possible presence of pressure gradients in the stripping cell. During the stripping cross section measurements cell pressure was monitored only at the point designated A in Fig. 13.

This procedure could result in erroneous cross section measurement if pressure gradients exist in the cell at any cell length. Using the arrangement shown in Fig. 13, the pressure was measured at point A and at five other positions in the cell for cell lengths of 6.25 and 2.5 cm. The ratio of the pressure measured at each of the five sampling points to the pressure measured at A was determined for cell pressures between 2×10^{-3} and 2×10^{-4} torr at both cell lengths. From the averaged results presented in Fig. 14 one can see that the pressure is fairly uniform in the 6.25 cm cell, being about 96% of the pressure measured at A. The measured pressure profile for the 2.5 cm cell reveals a small, but significant, pressure gradient with the

Figure 1.3. Cell pressure gradient testing apparatus. Cell pressure was measured at point A during stripping cross section measurement. Target gas introduction port and pressure-sensing port A are on opposite sides of cell, both of which are perpendicular to the side containing the five auxiliary pressure-sensing ports.

Figure 14. Measured cell pressure profile.

pressure measured at position 5, Fig. 13 being 85% of the pressure measured at A. On the basis of these measurements the adopted values of cell pressures were 85%, 89%, 92%, and 96% of the pressure measured at A for 2.5, 3.75, 5.0, and 6.25 cm cell lengths respectively.

Measurement of the neutral beam flux

Perhaps the most difficult aspect of the technique chosen for stripping cross section measurement is the necessity of measurements of the neutral beam flux. The simplest technique for monitoring the neutral beam flux is measurement of the current of secondary electrons ejected by the impact of the neutral beam on a metal surface. In order for this technique to provide an absolute measurement of the neutral flux, the secondary electron ejection coefficient γ^0 must be measured. For determination of γ^0 the initial intention was to use a pyroelectric detector similar to that described by Berkner et al. (1968). Such a detector was constructed and tested, and it is described in detail in Geis et al. (1976). The detector described therein, however, was discovered to be insufficiently sensitive for measurement of the small neutral fluxes obtained at the low energies used in the present stripping experiment. Hence, an alternate technique was devised for

determining the secondary electron ejection coefficients of the neutral detector surface, and the γ^0 measurement by the alternate technique checked against γ^0 measured with the pyroelectric detector.

Measurement of the secondary electron ejection coefficient γ^0 requires that one allow a known flux of neutral hydrogen atoms to strike the detector surface while one measures the current of secondary electrons leaving the surface. One method of obtaining a known flux of neutral atoms is to produce a fast neutral beam in the charge-transfer process

Since one X^+ ion is created for each fast hydrogen atom produced, the flux of fast neutrals can be inferred from a measurement of the number of X^+ ions produced. The present experiment applies this principle to produce a neutral flux with which to calibrate the neutral beam detector. Fig. 15 illustrates the apparatus used.

Electrodes C, D, and H formed an enclosure connected with the experimental vacuum chamber only through orifice B. The valving system shown in Fig. 15 permitted a pre-set flow of gas to be admitted to either the electrode structure or to the experimental chamber. For determination of γ^0 by

Figure 15. Gas cell used for determination of γ^0 .

the gas cell technique, orifice A was positioned on the beam axis, and a beam of protons was directed through apertures A and D. Gas (usually oxygen) sufficient to neutralize about 10% of the proton flux was introduced through valves I and J, resulting in a cell pressure of about 3×10^{-4} torr and a main chamber pressure of 1×10^{-5} torr. Electrodes C and E were biased at - 18 V, and all other electrodes were at ground potential.

All slow ions created between apertures B and D were collected on C. Complete collection is inferred from the observation that the current to electrode C saturated at a bias of approximately - 6 V. The slow ion current I^+ collected at C consisted of ions produced predominantly in the charge-transfer process

the cross section for which is about 10^{-15} cm^2 (Stebbins et al., 1964). Measured electron-production cross sections for H^+ incident on O_2 (McNeal and Birely, 1973) show that slow ions produced by collisional ionization should amount to less than 10% of the ion signal measured at electrode C, and as shown below, these additional ions were accounted for in the computation of γ^0 .

After the slow ion current was measured, electrode E

was raised to a positive potential sufficient to keep fast ions from passing through aperture D. The secondary electron current I^- leaving surface F was then measured. While most of the fast neutrals impinging on F were created by charge transfer between apertures B and D, some were formed in the main vacuum chamber. To account for fast neutrals formed outside the cell, the sequence of measurements set forth in Table I was executed and γ^0 was calculated from

$$\gamma^0 = \left(\frac{I_1^- - I_2^-}{I_1^+ - I_2^+} \right) \left(\frac{\sigma_{1,0} + \sigma_i}{\sigma_{0,1}} \right) \quad (17)$$

where $\sigma_{1,0}$ is the charge transfer cross section measured by Stebbings et al. (1964), and σ_i is the collisional ionization cross section for protons in O_2 reported by McNeal and Birely (1973).

As shown in Fig. 15 the rear element of the neutral beam detector was a lead zirconate titanate wafer, which could be used as a pyroelectric thermal detector. The hydrogen-atom fluxes available at the H^0 detector position shown in Fig. 7 were too small to permit in situ use of the pyroelectric detector; however, inserting the H^0 detector assembly in the beam line in place of the second 60° sector magnet afforded beam currents large enough that the pyroelectric detector could be used to check the gas cell

TABLE I

Quantity Measured	Cell Pressure (torr)	Chamber Pressure (torr)
I_1^+	3×10^{-4}	1×10^{-5}
I_1^-	3×10^{-4}	1×10^{-5}
I_2^+	1×10^{-5}	1×10^{-5}
I_2^-	1×10^{-5}	1×10^{-5}

results. Since use of the pyroelectric detector required that the beam be modulated, the beam was electrically chopped at 3.2 Hz by application of a square wave to the vertical deflection plates in the ion source chamber. With a gas cell pressure of 4×10^{-7} torr, the magnet was tuned so that a proton beam entered the cell. The proton current I_p and the output of the pyroelectric detector W_p were measured with a PAR 126 lock-in amplifier. Oxygen was admitted to the cell until a cell pressure of approximately 1×10^{-3} torr was attained. Electrode E was again used to stop un-neutralized ions and to collect secondary electrons from the surface F. The secondary electron current I_e^- leaving electrode F and the output of the pyroelectric detector W_H were both measured with the lock-in amplifier. Since ions and neutrals are equally efficient in depositing their energy in the pyroelectric element (Geis et al., 1976), γ^0 is given by

$$\gamma^0 = \frac{I_e^-}{W_H/W_p I_p} = \frac{I_e^- W_p}{W_H I_p} \quad (18)$$

The secondary electron ejection coefficients for hydrogen atoms measured by the pyroelectric and gas cell techniques are in excellent agreement as shown in Fig. 16.

Figure 16. Comparison of γ^0 measured by gas-cell and bolometric techniques.

Table II shows the gas cell results for γ^0 and the secondary electron ejection coefficients γ^+ for protons between 250 and 2000 eV. During the stripping cross section measurements γ^0 was measured periodically by the gas cell technique for H^0 energies from 250 to 3000 eV. Electrical breakdown in the gas cell feedthroughs made a measurement of γ^0 at 5000 eV impossible; it was therefore assumed that at 5000 eV $\gamma^0/\gamma^+ = 1.1$. The assumption is consistent with the trend of other data presented in Table II and with the data of Barnett and Ray (1972) and Pradel and Roussel (1974). It should be noted, however, that at relatively low projectile energies as used in this experiment the ratio γ^0/γ^+ may be dependent on the surface used and on the amount and composition of surface contamination.

There are several possible sources of experimental uncertainty associated with the calibration of the neutral beam detector by the gas cell technique. As will be shown below, the cell design permits estimation of the magnitudes of these uncertainties, and is such that the total uncertainty in the measured value of γ^0 is expected to be small.

Since the neutral flux reaching electrode F is taken to be related to the slow ion current arriving at electrode C by the equation

TABLE II

Energy (eV)	γ^+	γ^0	γ^0/γ^+
250	0.37	0.40	1.08
500	0.67	0.60	0.97
1000	1.12	1.11	0.99
2000	1.75	1.84	1.05
3000	2.12	2.30	1.08
5000	2.64	-	-

$$F = I_C \left(\frac{\sigma_{1,0}}{\sigma_{1,0} + \sigma_i^+} \right) , \quad (19)$$

the tacit assumption is made that the only possible sources of positive current at electrode C are stripping and collisional ionization processes occurring within the cell. Some other processes that can cause positive current at electrode C are discussed below.

Some fast positive ions are indubitably elastically scattered through sufficiently large angles that they reach electrode C; however, as shown in Appendix II, this process produces less than 1% of the positive current measured at C.

Another process that may lead to erroneous results in the determination of γ^0 is the production of photons in collisions of the H^+ ions with the O_2 in the cell. Vacuum ultraviolet photons can eject electrons from electrode C, and the current due to these electrons is indistinguishable from that caused by slow ions collected at C. The photon production cross sections, however, are fairly small, as is the probability of electron ejection per incident photon. For example, Birely and McNeal have measured the cross section for production of Lyman- α ($1216 \text{ \AA}$) photons in collisions of H^+ with O_2 in the energy range from one to

20 keV, and that cross section is about $5 \times 10^{-17} \text{ cm}^2$. Since the probability of electron ejection per Lyman- α photon is about 0.1, the number of electrons ejected is about three orders of magnitude smaller than the number of slow ions produced by the charge-transfer process

which has a cross section of about $1.5 \times 10^{-15} \text{ cm}^2$ in the energy range of interest (Koopman et al., 1968). Effects of the same order of magnitude are expected from vacuum ultraviolet photons emitted by O_2 molecules that are excited in collisions with protons. For example, Birely and McNeal have measured the cross section for $3914 \text{ \AA}$ emission induced by proton impact on an N_2 target and found the cross section to be less than $1 \times 10^{-17} \text{ cm}^2$ below 5 keV. The cross sections for formation of more highly excited states of the target are expected to be even smaller. Therefore, photon effects appear to be completely negligible with respect to the γ^0 determination.

Another source of electron emission from electrode C (hence, another possible source of experimental error) is potential emission of secondary electrons by the O_2^+ ions at the surface of electrode C. This process is not completely understood, but a fairly coherent review of thinking on

the subject is given by Kaminsky (1965). Potential emission has a large probability for He^+ ions impinging on a dirty surface, but for ions of lower ionization potential, the probability of potential emission of electrons is small. Fig. 17 shows secondary electron ejection coefficients for He^+ and Ar^+ ions striking a gas-covered stainless steel surface. The secondary electron ejection coefficient for argon is quite small at low energies, typically 0.01, while the secondary electron ejection coefficient for He^+ ions asymptotically approaches 0.2 as the ion kinetic energy is lowered. In the course of measurement of γ^0 the secondary electron ejection coefficient for H^+ ions on the rear surface of the neutral beam detector was also determined. These results also appear in Fig. 17 and indicate a low probability of potential ejection of secondary electrons by H^+ impact at low energies on a gas-covered surface. For ions with ionization potentials significantly lower than helium, it appears that the potential emission is relatively improbable and, thus, has also been neglected in the γ^0 measurement.

Further errors in the determination of γ^0 may arise from ionizing collisions of secondary electrons with the cell gas as they travel between electrodes F and E. The most probable process to cause difficulty is the electron-

Figure 17. Measured secondary electron ejection coefficients for ions on a contaminated metal surface.

impact ionization of the cell gas by these electrons.

Under the influence of the electric field between electrodes F and E, the ions are accelerated into electrode F, liberating more secondary electrons, which are in turn attracted to electrode E. Thus, a spurious current equal to the number $\underline{N}$ of ions created per unit time plus $\gamma\underline{N}$, the number of secondary electrons ejected by these ions, is added to the measured current of secondary electrons leaving F due to the impact of neutrals on F. Rapp and Golden (1964) have measured the electron-impact ionization cross sections in the energy range of interest (500 - 3300 eV) to be on the order of 10^{-16} cm^2 . Since the length of the path traveled by the secondary electrons between electrodes F and E is about an order of magnitude shorter than the path length over which neutral atoms are produced by charge transfer, the spurious ion current plus the secondary electron current from these ions is smaller than the neutral flux striking the back plate by about a factor of fifty and has also been disregarded in the determination of γ^0 .

In addition to the ionization produced by secondary electrons traveling between electrodes E and F, collisional ionization of the cell gas by the neutral beam passing through aperture D creates some slow ions and electrons between electrodes E and F. McNeal et al. (1970) have

measured collisional ionization cross sections for H^0 incident on O_2 between one and 20 keV. These cross sections are on the order of 10^{-16} cm^2 , and one therefore expects collisional ionization to contribute spurious currents at electrode F that are two orders of magnitude smaller than the current due to the neutral beam's secondary electron ejection at F.

Yet another error source may arise from differences in the path length over which neutral particles are created in the two biasing conditions used in the γ^0 measurement. As described earlier, the two biasing conditions are (a) (slow ion collection) with electrode C and E at - 18 V and all other electrodes at ground potential, and (b) with electrode C at - 18 V and electrode E at a potential sufficiently positive that no fast positive ions can pass through aperture D. The quantity measured in (a) is the slow ion current at C; and the quantity measured in (b) is the net positive current on electrode F which, one argues, is primarily due to secondary electrons created by impact of the neutral beam passing through aperture D.

Obviously the technique for measurement of γ^0 depends upon the assumption that the slow ion current collected in (a) is equivalent to the flux of neutral particles striking the back plate under condition (b). It has been argued

above that the current measured on electrode C is predominantly due to slow ions, but the equivalence of the measured slow ion current in (a) and the neutral flux in (b) can still be questioned on what are basically geometric grounds. As shown in Fig. 18 the path length for creation of slow ions in (a) is substantially different from the path length for creation of fast neutrals that can strike electrode F in (b). Electrode E collected the slow ions produced along the additional path length in (a). As shown in Fig. 19 the current to electrode E was relatively insensitive to the bias on electrode C, provided the biases on C and E were approximately equal. As noted, the ratio of the slow ion currents in configuration (a) to electrodes E and C was equal to the ratio of path lengths for creation of slow ions to the left and to the right of aperture D, namely 5 : 1. This fact, along with the independence of the slow ion current to E with respect to the bias on C, is taken to mean that the ions formed to the right of aperture D were not collected at C in configuration (a).

The exact path length for creation of neutrals in configuration (b) obviously depends on the position at which the ion beam is electrostatically reflected; the potential of electrode E is increased, the mirror point for the ions moves upstream as shown by the dotted path in

Figure 18. Ion path variation in gas cell under different biasing conditions.

Figure 19. Slow ion current to electrode E versus electrode C bias.

Fig. 18(b). Since the potential falls off very rapidly on the upstream side of aperture D, however, the ion beam mirrors very near aperture D, and one expects the effect of changing path length depicted in Fig. 18(b) to be very small. The small size of this effect is verified by the data presented in Fig. 20, where the current to electrode F is plotted as a function of bias on electrode E for cell pressures of 1×10^{-7} and 1×10^{-3} torr. Under the high cell pressure condition the current measured in region A is predominantly the current of un-neutralized positive ions striking electrode F. In region B the measured current is the current of positive ions plus the currents due to secondary electron ejection by fast ions and neutrals striking F. In region C the current is due to secondary electrons produced by fast neutrals striking surface F. Noting that the current measured in region C is independent of the bias on electrode E, one concludes that the change in neutral-creation path length induced by the variations in voltage on E is quite small and that the ions do, in fact, mirror very near aperture D.

An additional geometric problem relating to the equivalence of the slow ion current to C and the neutral flux to F is that immediately beyond aperture B there is a local enhancement of gas density due to gas streaming out

Figure 20. Ion stopping curves - γ^0 gas cell.

of the cell; and the slow ions formed in charge-transfer events between the proton beam and this gas, may not be completely collected by electrode C. As shown in Appendix I, however, the density enhancement is confined only to a small region extending only a couple of aperture diameters from the plane of aperture B. Examination of Fig. 36 reveals that the target thickness presented by this density enhancement is more than an order of magnitude less than the total target thickness of the cell, and the localization of the enhancement ensures that most of the ions created therein are collected by the penetration of the field from C through aperture B.

A further possible source of error in the determination of γ^0 by the gas cell technique is that some of the neutral atoms formed within the cell may fail to pass through aperture D because of angular scattering concomitant with their production by charge transfer. Fleischmann et al. (1969) have measured the differential cross section for the reaction

at energies between 50 and 300 eV. As shown in Fig. 18 aperture D subtends a half-angle of 2.8° when viewed from aperture B. Fig. 21 is a modified plot of Fleischmann's

Figure 21. Modified plot of Fleischmann, Young, and McGowan's data for differential cross section of $\text{H}^+ + \text{O}_2 \rightarrow \text{H} + \text{O}_2^+$.

differential cross section for the reaction described by Eq. 21 at a proton energy of 250 eV. The modification consists of multiplying Fleischmann's data by a factor of $\sin \theta$ so that the curve is representative of the total number of particles scattered at the stated ordinate. The ratio of the area under the curve below 2.8° to the area under the curve between 2.8° and 180° gives the fraction of neutral atoms lost by elastic scattering. This fraction is clearly less than 1%.

A final possible problem with the γ^0 determination stems from the fact that all the γ^0 determinations were made under relatively high cell pressure conditions, typically a few times 10^{-4} torr. One might wonder if the value of γ^0 were dependent on the pressure in the vicinity of the surface. It was verified that γ^0 is not pressure-dependent in the range of pressures used, by running a neutral beam into the γ^0 -measuring cell and measuring the secondary electron current at electrode F as a function of cell pressure. The measured secondary current decreases only 1% at the typical cell pressures used, and this decrease is entirely consistent with elastic scattering of the neutrals by the gas cell.

Based on all the above arguments, one concludes that systematic errors in the measurement of γ^0 by the gas cell

technique do exist and are such that the measurement of γ^0 may give a value that is too low by as much as 10%. Random errors in the γ^0 measurement are those associated with a succession of electrometer readings and amount to about $\pm 5\%$. The reproducibility of successive measurements of γ^0 is within this stated random error.

As mentioned earlier the values of γ^0 measured by the gas cell technique were compared with those measured by the pyroelectric detector described in Geis et al. (1976). The excellent agreement in the measured values of γ^0 by the two different techniques shown in Fig. 16 gives one additional confidence in the values of γ^0 determined by the cell technique.

In summary, the maximum systematic and random uncertainties are expected to be those set forth in Table III, from which one can set maximum error bounds of - 13%, + 33% on the reported cross sections.

TABLE III

	Systematic Uncertainty	Random Uncertainty
n	$\pm 3\%$	$\pm 1\%$
l	-	1%
I_P	- 10%, + 0%	$\pm 2\%$
I_O	+ 10%, - 0%	$\pm 5\%$

V

Results and Discussion

Electron loss by fast hydrogen atoms in a molecular gas M_2 may result from any of the following processes:

Cross sections for (b), (c), and (d) were measured by Afrosimov et al. (1972) for H incident on H_2 in the 5 to 50 keV energy range. At 5 keV the sum of the reported cross sections for (b), (c), and (d) is two orders of magnitude smaller than the electron-loss cross section reported here for 5 keV H^0 incident on H_2 ; therefore, the cross sections reported here are expected to be representative of reaction (a).

The results of the present experiment are summarized in Figs. 22 through 28, where the results of other investigators are plotted for comparison. In most cases the present results smoothly join the other results in the energy range where the measurements overlap; and where there is disagreement, these results tend to lie above those

KEY FOR FIGURES 22 THROUGH 28

Electron-Loss Measurements

- Present data
- △ Stier and Barnett (1956)
- Williams (1967)
- ▽ McClure (1964)
- Curran and Donahue (1960)
- ◇ McNeal and Clark (1969)
- ▲ Donahue and Hushfar (1961)
- Pilipenko and Fogel' (1962)

Total Negative Charge Production Measurements

- + Fleischmann and Young (1969)
- × McNeal et al. (1970)

Figure 22. Measured electron-loss cross sections for He compared with those of other investigators.

Figure 23. Measured electron loss cross sections for H_2 compared with those of other investigators.

Figure 25. Measured electron loss cross sections for O₂ compared with those of other investigators.

Figure 26. Measured electron loss cross sections for CO compared with those of other investigators.

Figure 27. Measured electron loss cross sections for CO₂ compared with those of other investigators.

Figure 28. Measured electron loss cross sections for CH₄ compared with those of other investigators.

of other investigators. As indicated in Chapter II one can usually ascribe this disagreement to incomplete product collection in earlier experiments.

It is worthwhile to compare the present results with the results of experiments in which the total negative charge produced in collisions between fast hydrogen atoms and various targets is measured. The negative charge production is due primarily to the two processes of stripping and target ionization, and measured stripping cross sections are expected to be less than or equal to the negative charge production cross sections. Figures 22 through 28 reveal that this relationship does hold between the present stripping data and the negative charge production data of Fleischmann and Young (1969) and McNeal et al. (1970). The difference between the measured electron production cross sections and the stripping cross sections should equal the cross section for target ion formation. These differences are, within mutual experimental error, consistent with the slow positive ion production cross sections measured by McNeal et al. (1970).

Recently Van Zyl has measured stripping cross sections for fast hydrogen atoms in the energy range of 50 to 3000 eV on He, H₂, and N₂ targets. His unpublished results agree well with the results of the present experiment for

He and H₂ targets; but his results for an N₂ target lie 60% above the present results at 250 eV, with the results of Van Zyl and the present measurement converging near 2000 eV. This discrepancy has not been fully resolved.

The present experiment has shown that at hydrogen-atom energies below 3000 eV all stripping cross sections decrease rapidly with energy, while the charge transfer cross sections for protons incident on atmospheric gases remain large below 3000 eV (Koopman, 1969; Stebbings et al., 1964). One may therefore expect that the degree of neutralization of the auroral hydrogen flux increases with decreasing particle energy below 3 keV.

Also, since the ratio of charge-transfer cross sections to stripping cross sections at solar wind energies is so large, charge transfer may be an effective means of removal of H⁺ from the solar wind plasma as it encounters the upper atmosphere of Venus. Currently Butler (1975) is studying the interaction of the solar wind with the Venusian atmosphere and is constructing a model of the interaction that will incorporate the stripping cross sections reported in this work.

VI

Theory

Theoretical treatment of collisional ionization at low energies is a particularly difficult problem; and below a collision energy of 5 keV theory and experiment are in serious disagreement, even for relatively simple collision partners. For example, the experimentally-determined cross section for the reaction

below 5 keV typically differs from the theoretical cross section by between a factor of two and two orders of magnitude, depending on the collision energy and the theory chosen for comparison.

Since collisional ionization at low energies is of some practical interest in atmospheric and thermonuclear research, the disagreement between theory and experiment probably does not arise from a lack of interest on the part of theoreticians, but simply reveals the difficulty of the theoretical problem.

Theoreticians have, however, made numerous approaches to the problem of collisional ionization. Some approaches have been purely classical, others quantum mechanical, and

still others have combined the classical and quantum treatments.

The earliest serious treatments of the problem were made simultaneously by Russek and Thomas (1958) and by Firsov (1958). Both treatments are completely classical and rely on a statistical model of the interacting atoms. Russek and Thomas treat ionization as a two-step process: first, the electron clouds of the collision partners interact, causing some of the translational energy of the colliding atoms to be transferred to excitations of their electrons. Russek and Thomas then assume that this electronic excitation is statistically distributed among the electrons and proceed to calculate the probability that any given number of electrons will acquire an energy large enough to escape its parent atom. Russek and Thomas represent their model as frictional heating of the electron clouds followed by "evaporation" of one or more of the electrons. Although the Russek-Thomas model (using two adjustable parameters) is successful in predicting ionization probabilities as a function of scattering angle in ion-neutral collisions at energies greater than 25 keV, it has not been applied to the evaluation of total cross sections for collisional ionization and stripping. In 1963 Russek published an extended version of his original theory,

introducing some quantum-mechanical features to the excitation and ionization mechanisms. The revised theory was again used for determination of ionization probability as a function of scattering angle for ion-atom collisions, and excellent agreement with experimental data was obtained without the use of empirically-adjustable parameters.

The Firsov theory is fundamentally a back-of-the-envelope calculation using the same physical interpretation of the collision process as the model of Russek and Thomas. Firsov determines the net momentum transfer between the colliding atoms by considering that electrons of one atom crossing an imaginary surface between the two atoms become "lost" in the other atom, giving up that part of their momentum associated with the net relative velocity of the colliding atoms. Appealing to a Thomas-Fermi model of the atoms for the appropriate number densities and electron velocities, Firsov calculates the total work done on each of the electron clouds during the collision and equates this work to the excitation of the electron clouds. The most important difference between the Russek-Thomas and Firsov theories is that Firsov merely calculates the probability of excitation of the electron cloud of one of the colliding atoms by an energy equivalent to the ionization potential of that atom. This simplification permits an

evaluation of approximate cross sections for ionization from first principles.

In terms of the accuracy of the results compared with the complexity of the necessary calculations, Firsov's technique is by far the most cost-effective theoretical approach to the determination of collisional ionization cross sections. Firsov's cross sections are almost always within an order of magnitude and often within a factor of two of the measured electron-loss cross sections. As shown in Fig. 29, however, Firsov's technique does not adequately predict the stripping cross section for hydrogen atoms in He at low energies: in fact, the Firsov theory is an abysmal failure for H - He collisions and is typically in error by an order of magnitude for collisions involving hydrogen atoms. This failure is reasonable in view of the dependence of the theory on the validity of the Thomas-Fermi atomic model, which is known to be a poor model for light atoms (Condon and Shortley, 1935).

Fleischmann et al. have compiled an immense amount of experimental data on electron-loss collisions (Fleischmann et al., 1972), and by systematic comparison of the measured cross sections with those given by the Firsov model, they have conclusively verified that the Firsov model fails in general for light projectiles at low energies in that the

Figure 29. Predictions of Firsov model for stripping of various projectiles in He and N₂ targets. From Fleischmann et al. (1972).

model produces neither the correct energy dependence nor the correct magnitude for the cross section.

In an effort to produce a theory that is more representative of the experimental data at low energies Fleischmann, Dehmel, and Lee (1972) have developed a semi-empirical scaling technique for absolute cross sections and collision energies that permits most electron-loss cross sections to be simply determined from a universal cross section curve that is itself determined by fitting extant experimental data.

Fleischmann, Dehmel, and Lee argue that the relatively rapid decrease of the stripping cross section at low energies may be more characteristic of a mechanism involving a single transition from the ground state into the continuum than of a gradual "frictional" heating of the atomic electrons during a collision. This group treats the ionization process as arising from a ground state-to-continuum transition excited by the time-dependent electric field seen by the projectile passing the target. By straightforward application of time-dependent perturbation theory Fleischmann et al. indicate that the relation of the cross section to the collision energy is entirely through functions of the parameter δ ,

$$\delta = E/E_i = E/MR^2 (E_i/13.6)^2 \quad (24)$$

where $\underline{E}$ is the projectile energy, $\underline{m}$ is its atomic mass number, $\underline{R}$ is an effective interaction radius, and E_i is the ionization potential of the projectile in eV. By plotting all measured cross sections for a particular projectile as functions of a reduced energy parameter ϵ and comparing the absolute values of the cross sections, Fleischmann et al. determine that the maximum values of the cross sections scale as $(Z_p^{2/3} + Z_t^{2/3})$, where Z_p and Z_t are the nuclear charges of the projectile and target respectively. By investigating the measured cross sections as a function of projectile ionization potential, Fleischmann et al. determine that the cross section magnitudes also scale as $(E_i/13.6)^{-\alpha}$, where α is a constant on the order of 0.5 and E_i is the projectile ionization potential in eV. Having determined these scaling relations for the magnitudes of the electron-loss cross sections, they replot all of the available cross section data scaled according to their semi-empirical scaling rules and show that almost all of the available stripping data falls within a factor of three of a universal stripping cross section curve given by

$$\sigma = 3.2 \times 10^{-14} \left(\frac{\epsilon}{\epsilon^{2/3} + 30^{2/3}} \right)^{1.2} \quad (25)$$

where $\epsilon = \frac{E}{M (E_i/13.6)^2 R_t^2}$, with $\underline{E}$ and $\underline{M}$ being the projectile energy and mass respectively and R_t being a dimension characteristic of the target atom.

Figure 30 scales the results of the present experiment according to the prescription of Fleischmann et al. for those targets for which Fleischmann gives a value of R_t . The renormalized measured cross section curves do in fact coalesce about a central curve parallel to, but above the "universal" curve of Fleischmann et al. The energy dependence of the present experiment's normalized data agrees with that predicted by Fleischmann et al. Comparing figures 22 and 23, one sees that the semi-empirical treatment of stripping results in a much better prediction of stripping cross sections at low energies than the Firsov theory, which fact may lend credence to Fleischmann's original suggestion that, at low energies, stripping proceeds by a single transition from the ground state into the continuum.

Reproduction of the energy dependence of the measured stripping cross sections by Fleischmann's model can not shed much light on the mechanism by which stripping occurs at low energies, since Mittleman and Wilets (1967) found essentially the same energy dependence for stripping processes using a very different theoretical model.

Figure 30. present stripping cross sections scaled to the prescription of Fleischmann et al.

The model used by Mittleman and Wilets (and by Demkov and Komarov, 1966) treated the stripping collision as if a very short-lived quasi-molecular complex were formed, and excitation of one of the electrons to the continuum proceeded through a series of transitions occurring near avoided curve crossings of states of the complex. Mittleman and Wilets invoke a statistical model of transition probabilities (originally developed for application in nuclear problems) that is expected to apply only in those regions of the potential curves of the quasi-molecule in which there is a fairly high density of states. Since transitions occur only to nearby states, Mittleman and Wilets deal exclusively with the flow of probability that a single electron is in an excited state having energy between E and δE . Treating the problem as one of diffusion of this probability up to the continuum, the authors arrive at a form for the energy dependence of the stripping cross section. Mittleman and Wilets' results are compared with the results of the present experiment in Fig. 31.

Flannery and Richmond (1973) have recently applied a "semiquantal" treatment to the calculation of electron loss of atomic hydrogen projectiles in rare gases. The semiquantal theory was originally devised for application to thermal collisions of highly-excited hydrogen atoms with

Figure 31. Comparison of present data with theoretical work of Mittleman and Wilets.

unexcited atoms and ions. Flannery's theory considers the collision between the target electron and the unexcited projectile in detail, while the only function of the target ion core is to provide a potential that determines the velocity of the electron involved in the interaction. This approach requires a detailed knowledge of the differential cross sections for elastic and inelastic scattering of the target electron by the projectile. These cross sections have been extensively studied, the information is readily available, and Flannery and Richmond choose Born-approximation results for the description of the electron projectile scattering. Flannery and Richmond's results are nearly identical to the Born-approximation results discussed below and agree well with experiments above about 25 keV. The authors point out that the similarity of the semiquantal results to those obtained by the full Born-approximation treatment of the collision may result from the adoption of electron scattering cross sections derived using the Born approximation, and that the semiquantal approach may yield better results at low energies if more sophisticated calculations of the electron-projectile interaction are incorporated into the calculation.

The only completely quantum-mechanical computations of electron-loss processes have been by means of the Born

approximation. Bates and Griffing (1955) and Boyd et al. (1957) discuss electron loss in H - H collisions. Levy (1969) and Bell et al. (1969) have computed cross sections for stripping of hydrogen projectiles incident on rare gases using the first Born approximation. As shown in Fig. 32, the Born approximation results agree with the experimental results for H + He above about 30 keV, while for the other rare gases poor agreement prevails at all energies. For stripping of hydrogen atoms in carbon, nitrogen, and oxygen targets Levy (1969) obtains good agreement with experiment only at energies above one meV, as shown in Fig. 33.

The reasons for failure of the Born approximation for stripping at energies below 100 keV are not well understood. The calculations shown in Fig. 34 explicitly neglect distortion and electron exchange, but the same sort of calculation (Levy, 1969) reproduces excitation cross sections for hydrogen atoms incident on He very well, down to about 3 keV. Levy and others (Winter, 1975) suggest that failure of the Born approximation may be due to neglecting the influence of excitation of many states of the incident projectile. For example, in computation of excitation cross sections for

Figure 32. Comparison of experimental results with Levy's Born-approximation

calculations of $\sigma_{1,0}$ for H incident on He.

Figure 33. Levy's Born-approximation calculations of $\sigma_{0,1}$ for H incident on O, C, and N. For purposes of comparison, the experimentally determined values of $\sigma_{0,1}$ for O₂ and N₂ were divided by two.

Figure 34. Comparison of experimental results with Levy's Born-approximation calculations of excitation cross sections for H incident on He.

Flannery (1969) has found that inclusion of the optically-allowed process

$$1S \rightleftharpoons 2P \rightleftharpoons 2S$$

increases the $1S \rightarrow 2S$ cross section by substantial amounts below 6 keV.

From the above discussion one sees that no truly adequate treatment of electron-loss collisions at low energies exists. Collisions in the energy range below one keV are particularly difficult to approach theoretically, since typical collision times correspond to the time required for a few electron orbits, and ionization is expected to take place within the framework of a short-lived collision complex whose wavefunctions have some molecular character. It may be that a satisfactory treatment of the process will only be possible through a perturbed-stationary-state treatment of the collision using a molecular basis. Such calculations are expected to be difficult and expensive, but are perhaps feasible up to collision energies of a few keV (Winter, 1975).

Appendix I

Calculation of Gas Density Near Gas Cell Exit Orifice

As pointed out in the text, it is sometimes desirable to know the approximate form of the density of gas in the vicinity of an orifice separating regions of different pressures. While this is a difficult problem to solve for all possible flow conditions, one can argue for a trivial solution under effusive flow conditions.

If the idealized gas cell shown in Fig. 35(a) is maintained at a sufficiently low pressure that the mean free path of gas molecules within the cell is much greater than the cell length l , and if the presence of the walls does not affect the angular distribution of velocity vectors of gas molecules within the cell, then the velocity vector angular distribution is the same for all points in the cell, and the distribution is completely isotropic.

If an aperture is opened in one wall as shown in Fig. 35(b) then the velocity vector angular distribution seen at any point in the cell becomes a function of position. In particular, those velocity vectors originating from that region of wall that was removed are no longer present at any point inside the cell. Therefore, insertion of the aperture reduces the flux through every point (X,Z) inside

the cell by a fraction ξ given by

$$\xi = \frac{\Omega_A}{\Omega_W + \Omega_A} = \frac{\Omega_A}{4\pi}$$

where Ω_A and Ω_W are the solid angles subtended by the aperture and the remaining wall at (X,Z) . The net flux j_0 through (X,Z) is modified by the presence of the aperture changing to j_A given by

$$j_A = (1 - \xi) j_0 = \frac{\Omega_W}{4\pi} j_0 .$$

Since for any gas molecule velocity $\underline{v}$, the flux j through (X,Y) is related to the density η due to molecules with velocity $\underline{v}$ at (X,Y) by

$$j = \eta v ,$$

and since insertion of the aperture modifies the fluxes for all velocities by the factor $(1 - \xi)$, then the density is modified by the same factor and is given by

$$\eta_A = \left(\frac{\Omega_W}{4\pi} \right) \eta_0 .$$

Outside the cell the same arguments apply in that an isotropic angular velocity distribution emerges from the aperture, and the density at any point outside the cell is again given by

$$\eta_A = \eta_0 \left(\frac{\Omega_W}{4\pi} \right). \quad (27)$$

In applying Eq. 27 one should note that outside the cell the aperture subtends a large solid angle, while the cell wall subtends a smaller solid angle. Equation 27 then states that the density missing at a point inside the cell simply shows up as a corresponding point outside the cell. Thus, Eq. 27 is a valid expression for the density on both sides of the aperture. The factor $\Omega_W/4\pi$ is readily evaluated at points along the Z-axis:

$$\begin{aligned} \frac{\Omega_W}{4\pi} &= \frac{2\pi \int_{\theta=0}^{\pi} \sin \theta \, d\theta}{4\pi} \\ &= \frac{1 + \cos \theta_0}{2}. \end{aligned}$$

Expressed in terms of $\underline{Z}$ and the aperture radius $\underline{r}$ the expression for density becomes

$$\eta\left(\frac{\underline{Z}}{\underline{r}}\right) = \eta_0 \left(\frac{1 + \frac{\underline{Z}}{\sqrt{\underline{r}^2 + \underline{Z}^2}}}{2} \right) = \eta_0 \left(\frac{1 + \frac{\underline{Z}/\underline{r}}{\sqrt{1 + (\underline{Z}/\underline{r})^2}}}{2} \right) \quad (28)$$

where $\underline{Z}$ equals zero at the position of the aperture.

Figure 35 shows a plot of this result. The numerator of Eq. 28 is clearly of odd parity; hence, areas A and A' in Fig. 36 are equal. Therefore, areas B and B' are equal,

Figure 35. Gas density profile near cell aperture.

Figure 36. Replot of Figure 35 showing equivalence of density depletion inside cell and density enhancement outside cell.

indicating that for the idealized cell considered the target thickness π defined by

$$\pi = \int_{\text{through cell}} n(z) dz$$

is the same for both cells shown in Fig. 34.

Of course most cells have two apertures, and the equality of target thickness for model cells with and without apertures no longer holds because the density along the axis is always less than the density η_0 at some point in the cell that is far away from the beam axis. The arguments used for the single-apertured cell are still valid, however, and the density at any point on the beam axis in the cell is still given by Eq. 27.

For a two-apertured cell of length $\underline{l}$ Eq. 27 has a particularly interesting consequence: if the cell's apertures have different diameters r_1 and r_2 ($r_1 < r_2$) and if one views the cell from the smaller-aperture end, at some distance Z_0 away from the smaller aperture the other aperture ceases to be visible; that is, Ω_W becomes zero. Consequently, under the premises set forth at the beginning of this appendix, beyond

$$Z_0 = \frac{r_1^2}{r_2 - r_1}$$

no gas from inside of the cell passes directly down the beam axis, and the so-called beam-line streaming is completely eliminated.

Appendix II

Insignificance of Elastic Scattering in γ^0 Measurement

In order to estimate errors in the γ^0 measurement due to elastic scattering of protons, the cross section for elastic scattering of 250 ev hydrogen projectiles by an angle sufficient to cause them to miss aperture D shown in Fig. 37 was measured. If the scattering occurs in the vicinity of aperture B, a scattering angle of about 2.8 degrees is required to cause the scattered particle to miss aperture D. By measuring the signal to the pyro-electric detector as a function of cell pressure, one determines the cross section for scattering beyond aperture D from the slope of a plot of I/I_0 versus cell pressure, as shown in Fig. 38. The "cross section" measured is obviously not the cross section for scattering by more than 2.8 degrees, but is merely a phenomenological cross section. "σ" is actually given by

$$"\sigma_S" = \int_B^F \sigma(Z) dZ$$

where $\sigma(Z)$ is the cross section for scattering by an angle sufficient to keep the particle from passing through aperture D. From the measurement of this cross section one can estimate the magnitude of the number of beam

Figure 37. Gas cell scattering geometry.

Figure 38. Beam attenuation vs. gas cell target thickness.

particles scattered through such large angles that they may strike electrode C.

Crandall, McKnight, and Jaecks (1973) argue that in the low keV energy range the elastic scattering can be treated classically, and that the differential cross section is given by the Rutherford scattering formula

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \frac{Z_{\text{eff}}^2 e^2}{2E} \frac{1}{\sin^4(\frac{\theta}{2})}$$

where Z_{eff} is an effective nuclear charge, and the potential is taken to be of the form $Z_{\text{eff}} \frac{e^2}{r}$, e is the electronic charge, and E is the projectile energy. This treatment is not expected to yield highly quantitative results in 250 eV collisions, but should suffice to show the importance of angular scattering in the γ -calibration experiment.

The cross section for scattering by angles greater than a certain angle θ_1 is given by

$$\sigma_{\theta_1} = \int_{\theta_1}^{\pi} \int_0^{2\pi} \frac{d\sigma}{d\Omega} \sin \theta \, d\theta \, d\phi = 2\pi \int_{\theta_1}^{\pi} \frac{d\sigma}{d\Omega} \sin \theta \, d\theta$$

Inserting the Rutherford scattering cross section, one gets

$$\sigma_{\theta_1} = \frac{1}{4} \frac{Z_{\text{eff}}^2 e^2}{2E} \int_{\theta_1}^{\pi} \frac{\sin \theta}{\sin^4(\frac{\theta}{2})} d\theta$$

Therefore, the ratio of the cross section for scattering by angles greater than θ_2 is given by

$$\frac{\sigma_{\theta_1}}{\sigma_{\theta_2}} = \frac{\int_{\theta_1}^{\pi} \frac{\sin \theta}{\sin^4(\frac{\theta}{2})} d\theta}{\int_{\theta_2}^{\pi} \frac{\sin \theta}{\sin^4(\frac{\theta}{2})} d\theta}$$

From the geometry shown in Fig. 38 at point A $\theta_1 = 12^\circ$ and $\theta_2 = 2.8^\circ$, and at point B, $\theta_1 = 90^\circ$ and $\theta_2 = 7^\circ$. Evaluation of the ratios $\sigma_{\theta_1}/\sigma_{\theta_2}$ at points A and B yields

$$\frac{\sigma_{\theta_1}}{\sigma_{\theta_2}} \approx \frac{1}{2000} \quad \text{at point A}$$

and

$$\frac{\sigma_{\theta_1}}{\sigma_{\theta_2}} \approx \frac{1}{200} \quad \text{at point B.}$$

Also, since

$$\frac{\sigma_{\theta_2}^{(A)}}{\sigma_{\theta_2}^{(B)}} \approx \frac{1}{10},$$

there is very little contribution to " σ_s " from points downstream of B. Therefore, since $\sigma_{\theta_1}/\sigma_{\theta_2}$ is always less than 1/200 in the interval between A and B and since the measured value of σ_s is 2 Å^2 , then the cross section for

scattering of ions into electrode C is $\lesssim 0.02 \text{ } \overset{\text{O}}{\text{A}}^2$; and since the charge-transfer cross section for the process

(which produces the majority of the ion current at C) is $\sim 20 \text{ } \overset{\text{O}}{\text{A}}^2$, the current of fast ions scattered into electrode C is completely negligible.

BIBLIOGRAPHY

- Afrosimov, V. V., Leiko, G. A., Mamaev, Yu. A., Panov, M. N.,
and Fedorenko, N. V., Sov. Phys. - JETP 35, 1070
(1972).
- Afrosimov, V. V., Leiko, G. A., Mamaev, Yu. A., Panov, M. N.,
and Vuiovich, M., Sov. Phys. - JETP 38, 243 (1974).
- Barnett, C. F., and Ray, J. A., Rev. Sci. Instrum. 43,
218 (1972).
- Bell, K. L., Dose, V., and Kingston, A. E., J. Phys. B 2,
831 (1969).
- Berkner, K. H., Myers, B. R., and Pyle, R. V., Rev. Sci.
Instrum. 39, 1204 (1968).
- Bethe, H. A., and Salpeter, E. E., Quantum Mechanics of One
and Two Electron Atoms, Berlin: Springer (1957),
pp. 286-287.
- Butler, D. M., private communication (1975).
- Condon, E. U., and Shortley, G. H., Theory of Atomic
Spectra, Cambridge Univ. Press (1935)
- Crandall, D. H., McKnight, R. H., and Jaecks, D. H., Phys.
Rev. A 7, 1261 (1973).
- Dehmel, R. C., Chau, H. K., and Fleischmann, H. H., At. Data
5, 231 (1973).
- Demkov, Yu. N., and Komarov, I. V., Sov. Phys. - JETP 23,
189 (1966).

- Dushman, S., Scientific Foundations of Vacuum Technique,
New York: Wiley (1949)
- Eather, R. H., Rev. Geophys. & Space Phys. 5, 207 (1967).
- Eubank, H. P., and Wilkerson, T. D., Rev. Sci. Instrum. 34,
12 (1963).
- Firsov, O. B., Sov. Phys. - JETP 36(9), 1076 (1959).
- Flannery, M. R., Phys. Rev. 183, 241 (1969).
- Flannery, M. R., Ann. Phys. (N.Y.) 61, 465 (1970).
- Flannery, M. R., and Richmond, B. L., Phys. Rev. 8, 2922
(1973).
- Fleischmann, H. H., Young, R. A., and McGowan, J. W., Phys.
Rev. 153, 9 (1967).
- Fleischmann, H. H., and Tuckfield, Jr., R. G., Nucl. Fus. 8,
81 (1968).
- Fleischmann, H. H., Dehmelt, R. C. and Lee, S. K., Phys.
Rev. A 5, 1784 (1972).
- Fleischmann, H. H., Barnett, C. F., and Ray, J. A., ORNL -
4954 (1974).
- Fogel', Ia. M., Ankudinov, V. A. Pilipenko, D. V., and
Topolia, N. V., Sov. Phys. - JETP 34, 400 (1958).
- Gerard, M., Ph.D. thesis, University of Paris (1975),
unpublished.
- Hayden, H. C., and Utterback, N. G., Phys. Rev. 135, A1575
(1964).

Johnstone, A. D., Planet Space Sci. 20, 292 (1972).

Kaminsky, M., Atomic and Ionic Impact Phenomena on Metal Surfaces, Berlin: Springer (1965)

Kingdon, J., Payne, M. F., and Riviere, A. C., J. Phys. B 3, 552 (1970).

Koopman, D. W., Phys. Rev. 166, 57 (1968).

Levy, II, H., Phys. Rev. 185, 7 (1969).

Loriot, G., and Moran, T., Rev. Sci. Instrum. 46, 140 (1975).

McClure, G. W., Phys. Rev. 134, A1226 (1964).

McClure, G. W., Phys. Rev. 166, 22 (1968).

McNeal, R. J., Clark, D. C., and Klingberg, R. A., Phys. Rev. A 2, 131 (1970).

McNeal, R. J., and Green, A.E.S., Bull. Am. Phys. Soc. 15, 427 (1970).

McNeal, R. J., and Birely, J. H., Rev. Geophys. & Space Phys. 11, 633 (1973).

Mittleman, M. H., and Wilets, L., Phys. Rev. 154, 12 (1967).

Pilipenko, D. V., and Fogel', Ya. M., Sov. Phys. - JETP 15, 646 (1962).

Pradel, P., and Roussel, F., Nucl. Instr. & Meth. 121, 111 (1974).

Rapp, D., and Golden, P. E., LMSC 6-74-64-12 (Lockheed Missiles and Space Co.) (1964).

Redhead, P. A., Hobson, J. P., and Kornelsen, E. V., The

- Physical Basis of Ultra-High Vacuum, London: Chapman & Hall, Ltd. (1968) pp. 253-366.
- Russek, A., Phys. Rev. 132, 246 (1963).
- Smith, K. A., Master's thesis, Rice University, Houston (1973).
- Solov'ev, E. S., Il'in, R. N., Oparin, V. A., and Fedorenko, N. V., Sov. Phys. - JETP 15, 459 (1962).
- Stebbins, R. F., Smith, A.C.H., and Ehrhardt, H., J. Geophys. Res. 69, 2349 (1964).
- Stier, P. M., and Barnett, C. F., Phys. Rev. 103, 896 (1956).
- Utterback, N. G., and Miller, G. H., Phys. Rev. 124, 1477 (1961).
- Van Zyl, B., private communication (1975).
- Winter, T. G., private communication (1975).