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TOTAL LOSS CROSS SECTIONS FOR D_2 MOLECULES PASSING THROUGH H_2 GAS

Young Pinckney Oliver
(M. S. Thesis)

April 1971

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TOTAL LOSS CROSS SECTIONS FOR D_2 MOLECULES PASSING THROUGH H_2 GAS

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ABSTRACT

We measured total loss (attenuation) cross sections for 3 to 45 keV D_2 molecules and D^0 atoms passing through H_2 gas. A light ion accelerator with an ion source operating in the PIG mode produced a 10^{-8} ampere D_2^+ current. Hydrogen gas in gas cell I neutralized a portion of the primary beam. Hydrogen in gas cell II re-ionized a fraction of the particles that had passed through the target cell. The target pressures varied between zero and twenty-five mtorr. All beam current measurements were made with Faraday cups and electrometers with integrators. Our values for the total loss cross sections for D_2 increased monotonically from 1.7×10^{-16} cm^2 at 3.3 keV D_2 energy to 3.0×10^{-16} cm^2 at 45 keV.

INTRODUCTION

In connection with the controlled fusion research at the Lawrence Radiation Laboratory, Berkeley, California, we have measured the total loss cross sections of D_2 molecules passing through H_2 gas with energies between 3 and 55 keV. Measurements by a different technique have been made by Tom Morgan in the D_2 energy range of 40 to 85 keV.[1] Calculations involving neutral particle injection into magnetic fields require the knowledge of loss cross sections for hydrogen molecules in hydrogen gas. For experimental reasons we use fast deuterium molecules with H_2 as the target gas. σ_{loss}, the total loss cross section for D_2, is defined as the sum of partial cross sections for all collision processes for which the scattered particle is not D_2.

In this experiment we often compare the loss cross sections of D_2 with those of H_2. We assume that total cross sections are essentially the same for D_2 or H_2 molecules of the same velocity. Due to momentum conservation, differential cross sections in the LAB system for D_2 on H_2 are more forwardly peaked than they are for H_2 on H_2. In the center-of-mass coordinate system, differential cross sections should be the same for both D_2 on H_2 and H_2 on H_2 because the extra mass of D_2 does not alter the electronic configuration significantly.

Our acceptance half-angle for scattering is .38 degrees. Only at low energies does large angle scattering become significant-largely due to elastic scattering. Changing the acceptance angle from .31 to .38 degrees had no effect on either the D_2 loss or the D loss cross sections at 5.5 keV. From this test and from other tests with varied collimation set-ups, we infer that loss due to large-angle scattering is negligible at energies down to 5.5 keV. These tests are described in detail in the appendix.

The following differential equation expresses the cross section for the case in which there are no sources of D_2 other than the original beam.

$$dN = -Nn\sigma\, dl$$

where N = flux of the beam in particles/unit area-unit time

n = number of target molecules/unit volume

l = target path length

σ = total loss cross section

The solution of the differential equation is $N = N_0 \exp(-nl\sigma)$. But $n = p/kT$ where p is the target gas pressure, k is the Boltzman constant, and T is the target gas temperature which remains constant.

By plotting a variable, that is proportional to N, versus the target pressure, we get a straight line on semi-log graph paper. The slope of this line is $d[\ln(N_0 e^{-pl\sigma/kT})]/dp$ which is equal to $-l\sigma/kT$. One may calculate σ if he knows the slope.

A D_2 molecule colliding with an H_2 molecule usually follows one of these four collision channels:[2]

Reaction 1: $D_2 + H_2 \xrightarrow{\sigma_1} D + D + H_2$ products

Reaction 2: $D_2 + H_2 \xrightarrow{\sigma_2} D_2^+ + e^- + H_2$ products

Reaction 3: $D_2 + H_2 \xrightarrow{\sigma_3} D^+ + D + e^- + H_2$ products

Reaction 4: $D_2 + H_2 \xrightarrow{\sigma_4} D^+ + D^+ + 2e^- + H_2$ products

The target molecules may be ionized, excited, or dissociated.

(the subscripts for the σ's refer to the reaction type)

The σ we measure includes all modes by which D_2 is converted into something else. Most other data is presented in terms of σ_{D^+}, $\sigma_{D_2^+}$, and σ_D where

$$\sigma_{D^+} = \sigma_3 + 2\sigma_4, \quad \sigma_D = 2\sigma_1 + \sigma_3 \text{ and } \sigma_{D_2^+} = \sigma_2$$

$$\sigma_{loss} = \tfrac{1}{2}\sigma_D + \tfrac{1}{2}\sigma_{D^+} + \sigma_{D_2^+} + \sigma_{neg} + \sigma_{other}$$

G. W. McClure has measured σ_{H^+} and $\sigma_{H_2^+}$ over a large energy spectrum, and has calculated σ_H at 10 keV (H_2).[3] We refer to this point in comparing our data with previous measurements. σ_{other} includes the loss of D_2 from the beam by non-ionizing and non-dissociative scattering at angles greater than .38 degrees. As mentioned previously this cross section is believed to be negligible for D_2 loss in this experiment. σ_{neg} includes those reactions in which negative ions are formed—$D_2 \rightarrow D^- + D^+$, and $D_2 \rightarrow D_2^-$. If we take the difference between σ_{loss} and $\frac{1}{2}\sigma_{H^+} + \frac{1}{2}\sigma_H + \sigma_{H_2^+}$ from McClure's data, we find that σ_{neg} is less than 1×10^{-17} cm^2 at 10 keV. Assuming a rough similarity between σ_{neg} and σ_{01}; the cross section for $D + H_2 \rightarrow D^- + \ldots$, for D on H_2, we expect σ_{neg} to be maximum at 10 keV and to decrease as the particle energy either increases or decreases.[4]

To further check our experiment for systematic errors we have also measured the loss cross section for D on H_2. This value is well known to very low energy ranges.[5-11] Our measurements compare favorably with the published values.

Quantum theory is not easily applied to give theoretical cross sections for our problems because the interaction time is comparable to the electron period. The Born approximation is valid only for energies much greater than those with which we are concerned. Our energy range is greater than that for which the adiabatic approximation is valid. The quantum mechanical formulation leads to a many-body problem that is almost insoluble in formal scattering theory. There are references available which address similar theoretical problems.[12-14]

METHOD AND APPARATUS

D^+ and D_2^+ ions created in a PIG (cold cathode Penning discharge) ion source,[15, 16] are accelerated across a 3 to 60 kV potential. A ninety degree bending magnet selects the species of interest to the experiment (see Fig. 1). As the ion beam passes through an H_2 filled cell, about 30 per cent of the ions are neutralized through charge exchange. The optimum gas pressure for this process for 10 keV H_2's is 20 mtorr with a neutralizer path length of approximately 5 cm. Electrostatic deflection plates sweep the remaining primary ions into a Faraday cup. This current, the master current, is fed into the integrator and is used to normalize the cup II current.

The neutral beam passes through the target cell into an ionizing chamber and then into a second analyzing tank. The gas pressure in the target cell is measured with a Barocel capacitance manometer. High voltage between parallel wires in the target cell deflects ninety per cent of the ions out of the beam line. A two kilogauss permanent magnet deflects the rest of the ions before they enter the ionizing region. About five per cent of the remaining particles are re-ionized in the ionizer cell. Deflector plates sweep these ions into the Faraday cup. The pressure in the ionizer region is kept at some constant pressure between .5 and 8.0 mtorr throughout a single cross section measurement so that the current measured in the Faraday cup is proportional to the number of neutrals passing through the target cell. Scaled drawings of the apparatus are presented in Figs. 2 and 3.

We measured the cross section at each energy by plotting attenuation curves with respect to target pressure. We "tuned" the beam on the accelerator by varying the source conditions, focusing current, bending magnet current, and deflection voltage so as to obtain the strongest possible steady beam. For a well-tuned beam a typical current measured in Faraday cup I was 5×10^{-11} amperes.

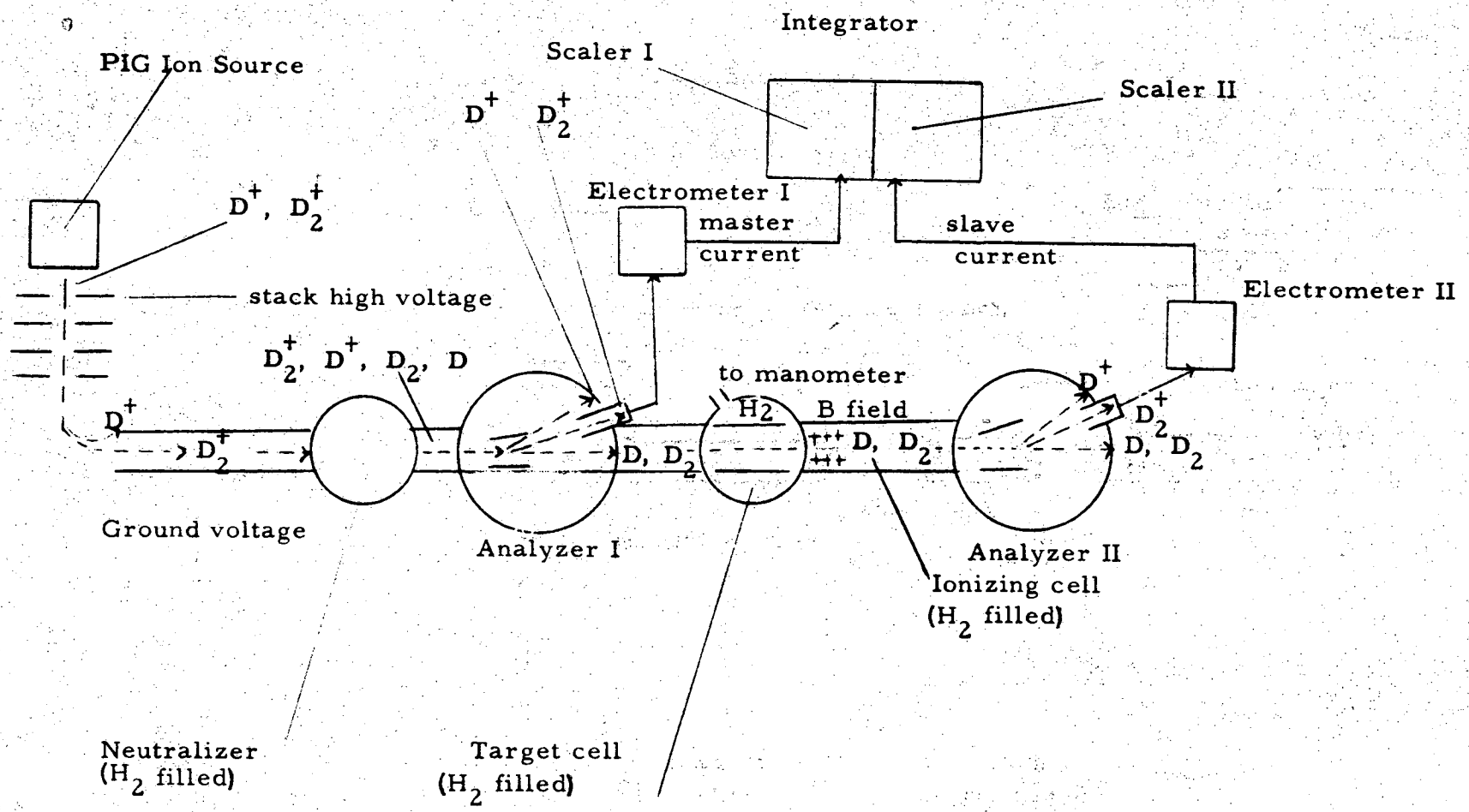
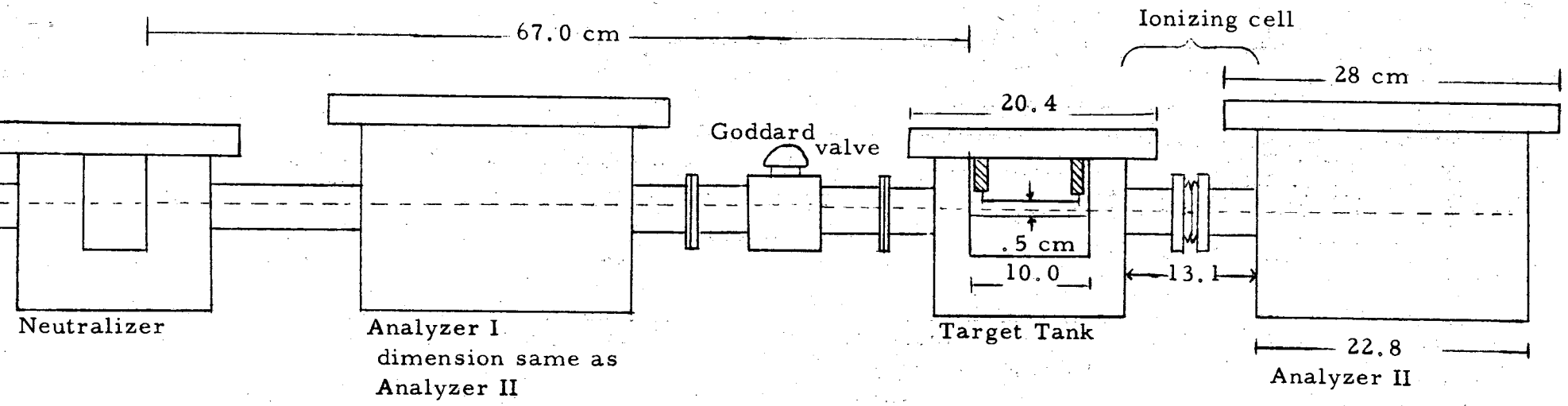

Integrator
Scaler I
Scaler II
PIG Ion Source
D^+ D_2^+
D^+, D_2^+
Electrometer I
master
current
slave
current
Electrometer II
stack high voltage
D_2^+, D^+, D_2, D
to manometer
H_2
B field
D^+
D_2^+
D, D_2
D, D_2
D, D_2
D^+
D_2^+
D, D_2
Ground voltage
Analyzer I
Analyzer II
Ionizing cell
(H_2 filled)
Neutralizer
(H_2 filled)
Target cell
(H_2 filled)

Fig. 1



1/5 scale

All dimensions in cm.

Fig. 2

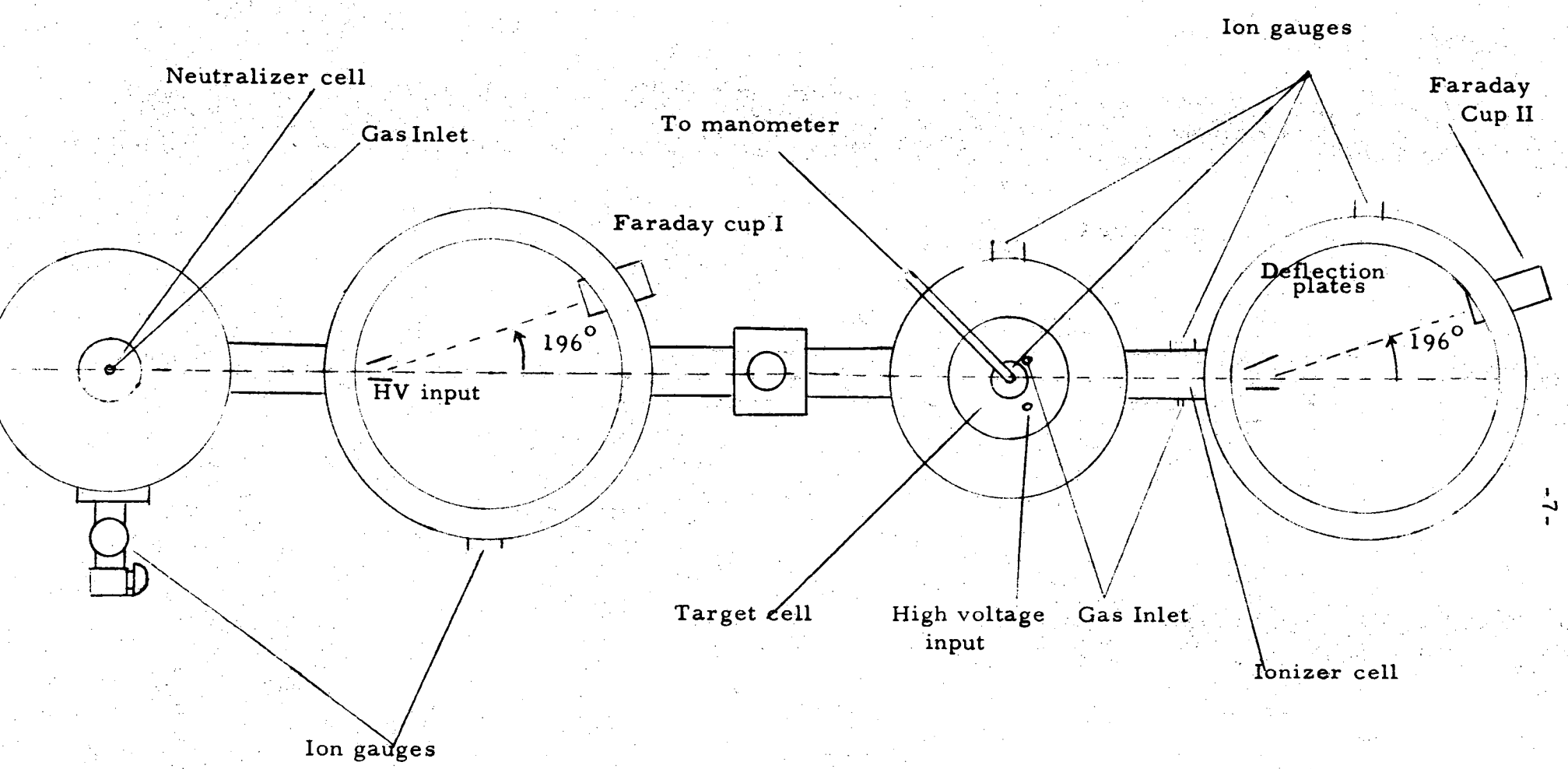

Neutralizer cell
Gas Inlet
Faraday cup I
196°
HV input
Ion gauges
To manometer
Target cell
High voltage input
Gas Inlet
Ion gauges
Faraday Cup II
Deflection plates
196°
Ionizer cell

Fig. 3

A typical D_2^+ current in cup II was 10^{-12} amperes. The Keithley electrometer is capable of measuring ion currents as low as 10^{-14} amperes. In order to measure the 3 keV D_2 loss cross section, we measured an unattenuated cup II current of 1.9×10^{-13} amperes. This weak ion current set the lower limit on our energy range. At low energies our ion currents were very steady. This indicated that all the current and voltage supplies were well regulated and the source conditions were stable.

In a typical run we zeroed the electrometers and began with two or three background pressure counts. Typical background target pressures were 1×10^{-5} torr. Typical pressures in the region immediately outside of the target cell were 3.0×10^{-5} torr.for a target cell pressure of 15 mtorr. After this we made counts at five or six pressures between 0 and 25 mtorr of target pressure. We repeated this procedure two or three times and ended with a background count. Then we closed a valve to shut off the beam entering the target cell. We checked for background currents due to discharges or current leaks. Typical background currents were 10^{-14} amperes. We always corrected our attenuation counts for the background currents. Immediately after each run we plotted the counts versus pressure on semi-log graph paper. We checked the graph for linearity and the calculated cross sections for reasonability. Figure 4 contains a sample attenuation plot.

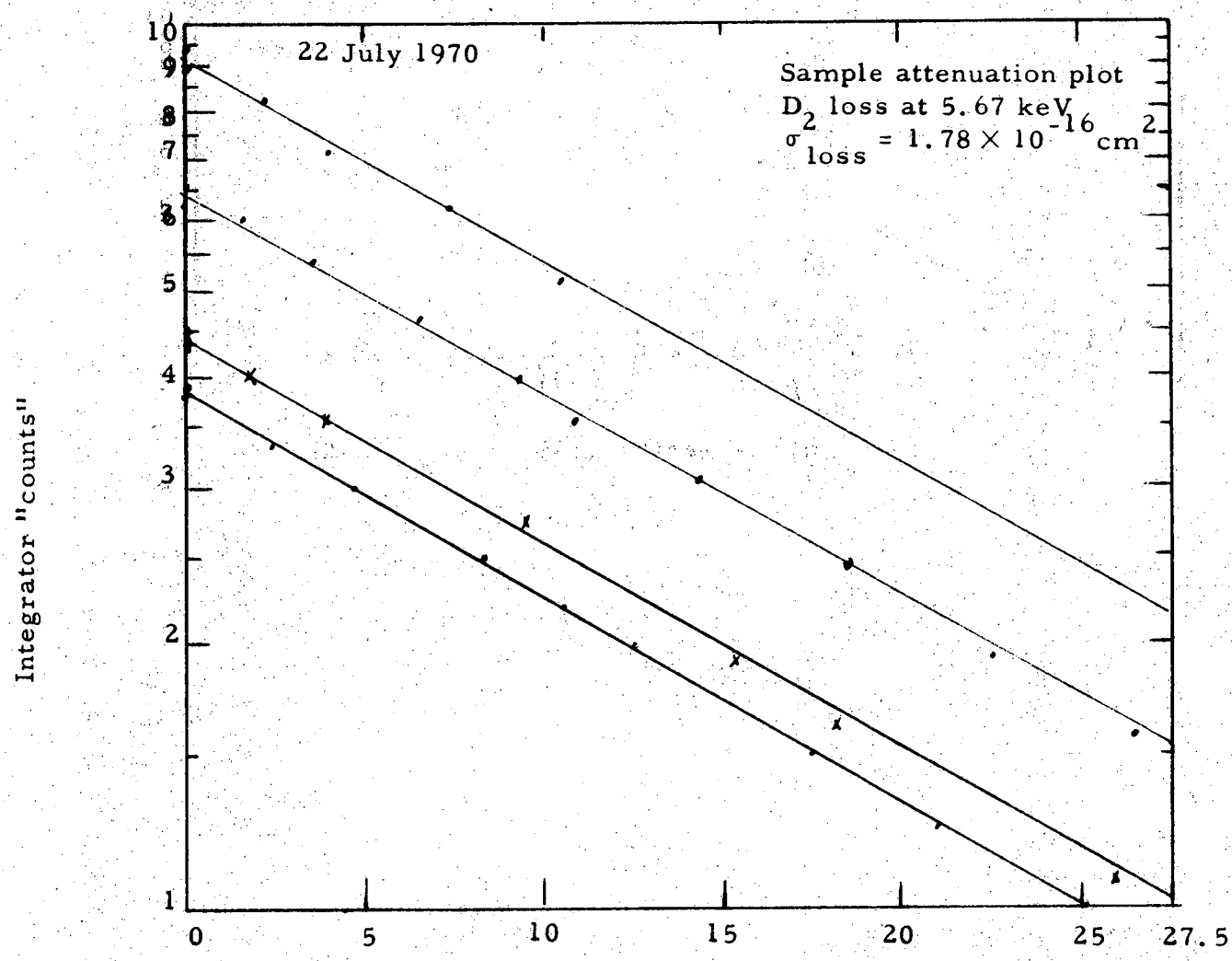


Fig. 4 Target Pressure (mtorr)

EXPERIMENTAL RESULTS

Our measurements extend the range of known H_2 loss cross sections from 20 keV down to 1.6 keV. McClure's measurements of σ_{H_2} and σ_{H^+} went down to 4 keV but he calculated σ_H for only one energy — 10 keV. In Fig. 5 we compare our measurements with McClure's single point and previous measurements at higher energies by Tom Morgan, who used scintillation detectors for his particle counting.[1]

In Fig. 6 we show our values of σ_{loss} for H on H_2. We made this measurement as a general check of the accuracy of our technique. σ_{loss} is equal to $\sigma_{01} + \sigma_{0,-1} + \sigma_{other}$. σ_{other} is due to non-ionizing (such as elastic) scattering and is shown in the appendix to be negligible. The effect of collimation size on the cross sections is discussed. In Fig. 6 we obtain our values of σ_{01} by subtracting McClure's values for $\sigma_{0,-1}$ from our values for σ_{loss}. Loss of particles due to large-angle scattering would tend to make McClure's measurements of σ_{01} too low and would tend to make our measurements too high because McClure is measuring H^+ production whereas we are measuring D loss. One may be quite certain that the true value is bounded by these two measurements which imply a maximum uncertainty of 20 to 27 per cent of a few keV and 5 to 10 per cent at 20 keV.

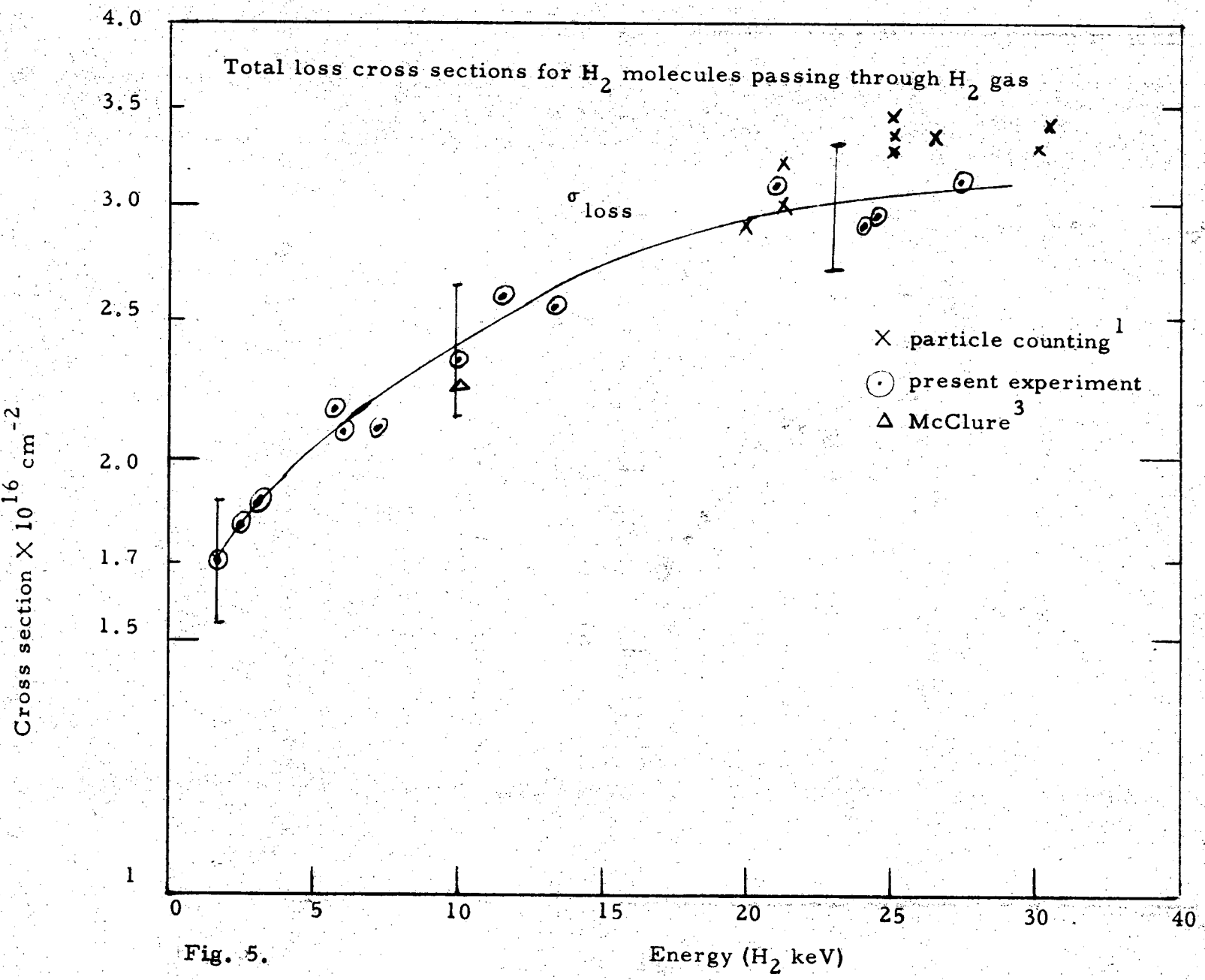

Total loss cross sections for H_2 molecules passing through H_2 gas
σ_{loss}
× particle counting[1]
⊙ present experiment
Δ McClure[3]
Cross section × 10^{16} cm^{-2}
4.0
3.5
3.0
2.5
2.0
1.7
1.5
1
0
5
10
15
20
25
30
40
Energy (H_2 keV)

Fig. 5.

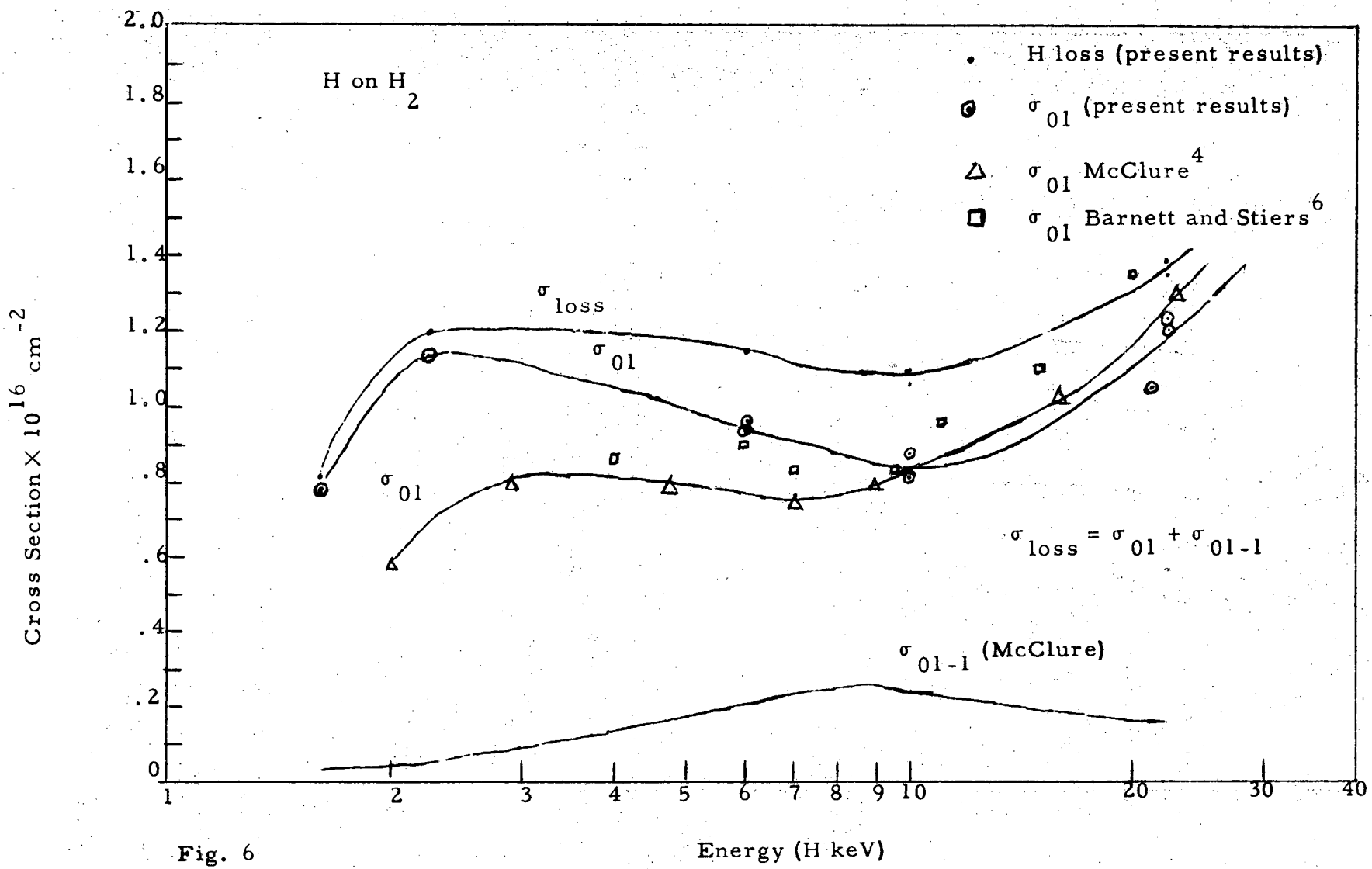

H on H_2
H loss (present results)
σ_{01} (present results)
σ_{01} McClure[4]
σ_{01} Barnett and Stiers[6]
σ_{loss}
σ_{01}
σ_{01}
$\sigma_{loss} = \sigma_{01} + \sigma_{01-1}$
σ_{01-1} (McClure)
Cross Section $\times 10^{16}$ cm^{-2}
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
1
2
3
4
5
6
7
8
9
10
20
30
40
Energy (H keV)

Fig. 6

DISCUSSION AND CONCLUSIONS

Cross sections for the loss of 3.2 to 55 keV D_2 molecules passing through hydrogen gas have been measured with an estimated uncertainty of 9 per cent. Specific sources of uncertainty are described in this section.

We determined the particle energy by assuming the particle to be accelerated through the source extractor voltage plus the stack voltage. Although the stack voltage is very accurately measured it is not possible to measure the exact extractor voltage because the surfaces of the ion source are surrounded by a plasma sheath of unknown potential. For this reason we have plotted the hall current in the bending magnetic field versus the estimated energy (Fig. 7). The plot should be linear on log-log paper with a slope of 1/2. The actual plot is quite linear for both D and D_2. The slope for D is .520 and the slope for D_2 is .517.

Examination of the graph on Fig. 7 shows that a constant increment or decrement (as in a plasma sheath) of as much as 300 eV to each of the energy points would not cause the curve to appear non-linear. The voltage drop across the plasma sheath is estimated to be 200 volts,[17] which is less than the 300 volts uncertainty. A 300 eV uncertainty in the low energy region gives a 10 per cent energy uncertainty in that region. In the 2 keV to 10 keV range a 10 per cent energy uncertainty gives a 1 per cent uncertainty in the σ_{01} cross sections for H and a 2 per cent uncertainty in the H_2 loss cross sections.

Our experiment requires only that electrometer I measure a constant fraction of the primary beam and that electrometer II measure a constant fraction of the secondary beam for each attenuation plot. The best way to check this is to make repeated counts at a given target pressure. Errors due to these fluctuations were less than 1 per cent.

Our pressure measurements were made with a Baracel capacitance manometer. On previous experiments this type of manometer

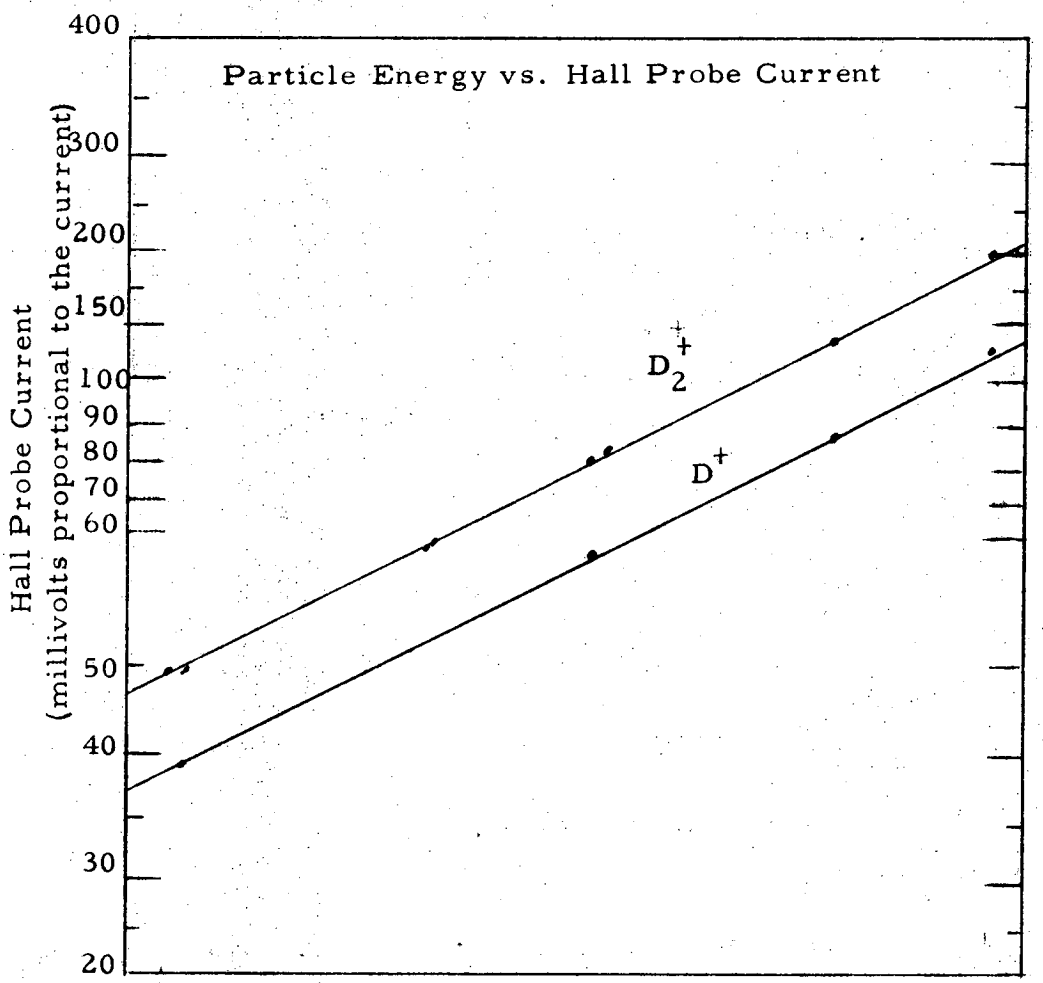


Fig. 7 Particle Energy (keV)

has been determined to be accurate to within 5 per cent.[18] The linearity of the plots and the agreement with other cross section measurements confirm this estimate.

We estimate the effective target length to be 8.86 cm. The outside length in the target cell is 10.16 cm. The inside length is 7.55 cm. We estimate the effective target length to be the mean of these two lengths with an uncertainty of 5 per cent.

Errors due to impurities in the target gas are believed to be negligible. Frequent checks of the vacuum system enabled us to be sure that no air was leaking into the target cell. Our gas source was a fresh bottle of pure H_2. Close agreement with previous measurements at energies greater than 9 keV tends to confirm this belief.

The curve through our cross section values on Fig. 5 has been drawn free hand so that it is smooth and the sum of the deviations from the curve is nearly zero. The standard deviation of D_2 loss cross sections from this curve is $.076 \times 10^{-16}$ cm^2. This gives a 4.4 per cent statistical uncertainty at the low energy end of the range and a 2.5 per cent uncertainty at the high energy end.

Considering all potential sources of error we estimate the total uncertainty of our cross section measurements to be 9 per cent. (See the error analysis section of the appendix).

ACKNOWLEDGMENTS

I wish to thank Tom Morgan for his considerable help in planning, discussing, and running this experiment. Also, Dr. Robert V. Pyle for his active support, supervision, and encouragement; Dr. Klaus H. Berkner for many valuable discussions on both the theoretical and experimental aspects of the problem; Vincent J. Honey and J. Warren Stearns for their help in the construction and operation of the equipment; and Mary L. Long and Ellen E. Cimpher for their patient help in typing the manuscripts.

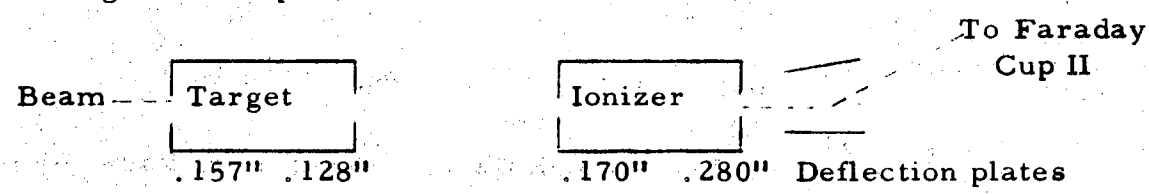
This work was done under the auspices of the U. S. Atomic Energy Commission.

APPENDICES

Collimation

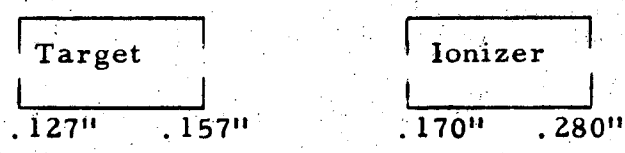
To make sure that particle loss due to large-angle scattering was negligible we made the following collimation changes and observed their effects.

I. Original Set-up



The dimensions refer to the aperture size. At 19.8 keV the D loss cross sections were 1.1×10^{-16} cm^2 and 1.06×10^{-16} cm^2 on two independent measurements.

II.



At 19.9 keV the D loss cross section was 1.1×10^{-16} cm^2.
At 11.9 keV the D loss cross section was $1.21 \times 10^{-16} cm^2$ considerably greater than McClure's value.

III.

At 11.9 the D loss cross section was 1.35×10^{-16} cm^2 with an ionizer pressure of 4 mtorr.

IV.

At 11.9 keV the D loss cross sections were 1.22×10^{-16} cm^2 with P_I = 2.8 mtorr (P_I = ionizer pressure), 1.15×10^{-16} cm^2 with P_I = 1.26 mtorr, and 1.14×10^{-16} cm^2 with P_I = .72 mtorr. The fact that σ_{loss} remained constant for the lower ionizer pressures is a good indication that we are not losing many neutral particles through large-angle scattering.

V.

At 11.9 keV the D loss cross sections were 1.2×10^{-16} cm^2 with P_I = 1.08 mtorr, 1.1×10^{-16} cm^2 with P_I = .70 mtorr, and 1.3×10^{-16} cm^2 with P_I = 3.6 mtorr. The loss cross sections for 11.9 keV D_2's were 2.04×10^{-16} cm^2 with P_I = 4.0, 2.2, 1.02, and 6.0 mtorr and 2.05×10^{-16} cm^2 with P_I = .42 mtorr. At 5.5 keV the loss cross sections remained constant for several different ionizer pressures. The acceptance half-angle as defined in Fig. 8 is .31 degrees. The 5.5 keV D loss cross sections were 1.2×10^{-16} cm^2 with P_I = 3.0, 1.8, and 5.8 mtorr. The 5.5 keV D_2 loss cross sections were 1.78×10^{-16} cm^2 with P_I = 2.8 and 5.6 mtorr.

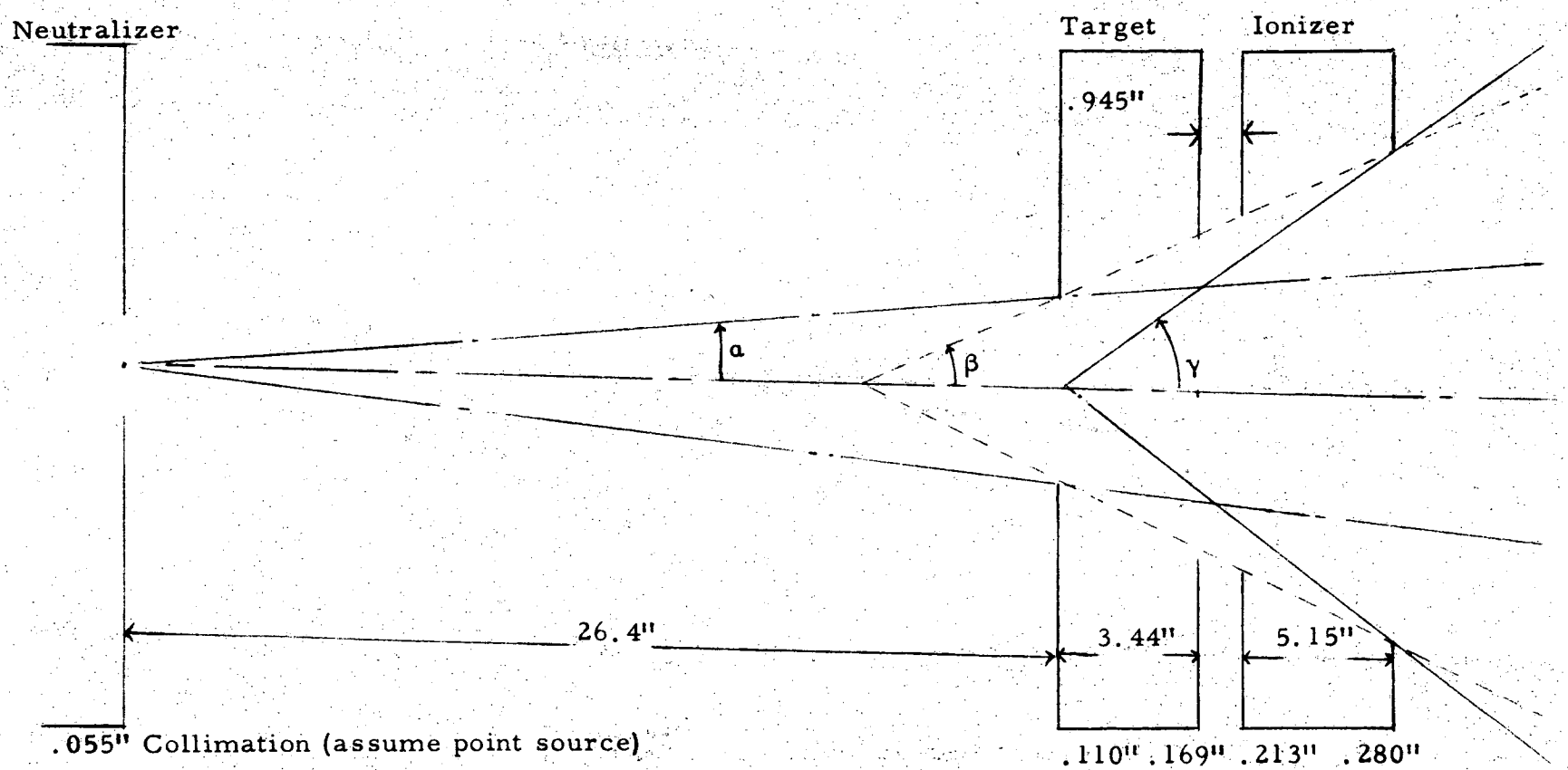


Fig. 8

Collimation Diagram
10 X vertical scale
1/5 horizontal scale

$\alpha = .1156^{\circ}$
$\beta = .502^{\circ}$
$\gamma = .760^{\circ}$
Acceptance half-angle = $\beta - \alpha = .38^{\circ}$

VI.

We increased the acceptance half-angle from .31 to .38 degrees for the final collimation set-up. The 5.5 keV D loss cross sections was 1.2×10^{-16} cm^2 with P_I = 1.88 mtorr. The D_2 loss cross sections were 1.78×10^{-16} cm^2 with P_I = 1.88 and 3.0 mtorr. We conclude that D loss and D_2 loss due non-ionizing and non-dissociative scattering such as elastic scattering is negligible down to 5.5 keV D and D_2 energy. At 3.35 keV the D loss cross section was $.815 \times 10^{-16}$ cm^2 with P_I = 6.6 mtorr. At 3.35 keV the D_2 loss cross section was 1.72×10^{-16} cm^2 with P_I = 6.0 mtorr. We have no proof that we are not losing neutral particles due to large-angle scattering at this low energy point. Comparing the shape of our curve for σ_{01} with that of McClure and Barnett and Stier in this energy range leads us to believe that we are not losing very many. As a final check we re-measured the D_2 loss cross section at 42.1 keV. Our value was 3.14×10^{-16} cm^2 which falls within our uncertainty at that energy.

Error Analysis

We take the total uncertainty to be equal to the square root of the sum of the squares of the individual uncertainties.

$$\sigma = \frac{SkT}{l}$$

where S = the slope on the semi-log plot

$S = \frac{\ln 2}{P_{1/2}}$ where $P_{1/2}$ is the target pressure increase which attenuates the beam by 1/2.

$\sigma = \frac{kT\ln 2}{P_{1/2}l}$ $\quad d\sigma$ = absolute uncertainty for σ

$\frac{d\sigma}{\sigma}$ = fractional uncertainty for σ

$\frac{d\sigma}{\sigma} = \frac{(\frac{\partial \sigma}{\partial q})\, dq}{\sigma}$ is the fractional uncertainty in σ due to the absolute uncertainty dq in parameter q.

$$\frac{d\sigma}{\sigma} = \sqrt{\left(\frac{dT}{T}\right)^2 + \left(\frac{dP_{1/2}}{P_{1/2}}\right)^2 + \left(\frac{dl}{l}\right)^2}$$

The total uncertainty for σ also includes a 4 per cent uncertainty with respect to the internal consistency of the measurements (this is the statistical uncertainty discussed in the Discussion and Conclusion section) and a 2 per cent uncertainty in σ due to a 10 per cent uncertainty in the energy measurements at low energies.

In Tabular Form

Parameter	Uncertainty	Corresponding σ Uncertainty
Temperature	2%	2%
Pressure	5%	5%
Target Length	5%	5%
Internal Consistency	4%	4%
Energy	10%	2%

The estimated total uncertainty for both the D loss and the D_2 loss cross sections $= \sqrt{2^2 + 5^2 + 5^2 + 4^4 + 2^2} = \sqrt{74} = 8.6\%$ or 9%.

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FIGURE CAPTIONS

Fig. 1. Schematic drawing of the experimental arrangement. The pressures in the neutralizer and ionizing region are kept constant. One or more "counts" are made at each target pressure point. Scaler II "counts" (integrates the current) as long as Scaler I is counting. Scaler I counts until a preset accumulated charge is reached.

Fig. 2. Side view of the experimental apparatus. A one kilogauss permanent horseshoe magnet is placed between the target tank and and the first flange to the right. The magnetic field deflects all charged particles remaining in the beam. The right two-thirds of this pipe is the ionizing region.

Fig. 3. Top view of the experimental apparatus.

Fig. 4. Integrator "counts" are plotted versus target pressure for 5.67 keV D_2. This is the raw data from four experimental runs, at four different ionizer pressures.

Fig. 5. H_2 loss cross section versus the particle energy. We compare our results with the McClure's data point at 10 keV and with Tom Morgan's results on previous measurements. Tom Morgan used the same experimental apparatus but detected the D_2's with a scintillation detector.

Fig. 6. The total loss, electron loss, and electron capture cross sections for H^0 atoms versus H^0 energy. We are comparing our values for σ_{01} with those of McClure, and Barnett and Stier.

Fig. 7. Estimated particle energies versus the current of the Hall probe in the bending magnet's field. Theoretically the plot should be linear with a slope of 1/2. The true slope for D_2^+ is .517 and the true slope for D^+ is .520.

Fig. 8. Schematic diagram of the final collimation setup. The angles are magnified fifty times their true size. Neutral particles near the center that are deflected less than .76 degrees will be detected. All neutral particles deflected less than .39 degrees will be detected.

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