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Measurement of the Cross Section for
Resonant Charge Exchange of He\textsuperscript{+} on He\textsuperscript{0}
With a Merged Beams Apparatus

by

Michael William Geis

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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I recommend the Silver Clustered Drill Bit to Jim Godwin for valor and strength in constructing difficult vacuum chambers.
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CHAPTER I
INTRODUCTION

A knowledge of many ion-neutral reaction cross sections for collisional energies between 0.05 ev and 10 ev (500 to $10^5$ O K) are important in predicting the properties of planetary atmospheres, especially in regions where heating of the atmosphere by solar radiation is important. In such regions the heavy particle temperatures are often 750 o K or higher. This thesis reports the first measurement of a cross section using a newly completed merged beams apparatus that was specifically designed to study this energy region for ion-neutral reactions of aeronomic interest.

The merged beams technique by superimposing two particle beams of convenient laboratory energies (500 ev to 10 kev), makes it possible to measure reaction cross sections in this low energy region where it was difficult with other methods. By adjusting the velocities of the beams, collisional center of mass energies between the particles of the two beams can easily be varied from
less than 0.05 eV to 200 eV. Several experimenters have previously constructed merged beam apparatuses and measured cross sections for rearrangement reactions
\[ \text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H}^{(1)}, \]
and for charge exchange reactions
\[ \text{Ar}^+ + \text{Ar}^o \rightarrow \text{Ar}^o + \text{Ar}^+(2). \]
A description of some of these devices is given by Neynaber\(^{(3)}\).

The choice for the first reaction to be investigated with the recently constructed merged beams apparatus, which has been discussed by Geis\(^{(4)}\) and by Smith\(^{(5)}\), was based on two factors. First the apparatus had not been proven to be able to produce reliable cross section data. Therefore data from the chosen reaction should have previously been published in order to check the results of the merged beam apparatus. The second factor is one of technical convenience. The primary beams of reactant species should be easily formed in a pure energy state. Further, the reaction should have a large cross section \((\sim 10 \text{ \AA}^2)\) so that favorable signal-to-noise ratios can be obtained.

Of the possible reactions to be investigated the
charge exchange reaction,

\[ \text{He}^+(1s) + \text{He}(1s^2) \rightarrow \text{He}(1s^2) + \text{He}^+(1s) \]

was chosen. As shown in Figure I-A, not only is there considerable information on the \( \text{He}^+ \) on \( \text{He}^0 \) reaction, but there are gaps in the available experimental data between 30 ev and 100 ev, and below 0.5 ev which the merged beams technique can eliminate. The broken line curves in Figure I-A represent experimentally obtained cross sections, while the solid line curves were determined theoretically. Further, it was felt that the experimental advantages of a large cross section and easily formed ground state primary beams make the study of this reaction desirable for demonstrating the performance of the apparatus.

Since the primary purpose of this thesis is to demonstrate the reliability of the recently constructed apparatus, the next two chapters are concerned with the apparatus and the measurement of a cross section. Chapter IV discusses the consistency checks on the apparatus. In Chapter V the cross section measurements from the merged beams apparatus are compared with previous experimental and theoretical data. A brief discussion of the experimental and theoretical techniques used to obtain previous data is also given.
CHAPTER II

MERGED BEAMS TECHNIQUE AND APPARATUS

To understand some of the advantages of the merged beams method a brief description of the technique is given. Consider two primary particle beams labeled I and N which have been merged so that the beams are superimposed. Then the center of mass collisional energy, $E_{cm}'$, of the particles in beam I with those of beam N is given by

$$E_{cm}' = \frac{\mu}{2} |\vec{v}_I - \vec{v}_N|^2,$$  \hspace{1cm} \text{II-A}

where $v_I$ and $v_N$ are the laboratory velocities of the particles of beams I and N respectively and $\mu$ is the reduced mass. If the particles of the beams interact at some angle $\theta$ in the laboratory frame then

$$E_{cm}' = \frac{\mu}{2} [v_I^2 + v_N^2 - 2v_I v_N \cos \theta].$$  \hspace{1cm} \text{II-B}

If $\theta \ll 1$, then $\cos \theta \approx 1 - \theta^2/2$ and

$$E_{cm}' = \frac{\mu}{2} [(v_I - v_N)^2 + \theta^2 v_I v_N].$$  \hspace{1cm} \text{II-C}

Rewriting Eq. II-C in terms of the laboratory energies of the two beams $E_I$ and $E_N'$.
\[
E_{\text{cm}} = \mu (\sqrt{E_I/m_I} - \sqrt{E_N/m_N})^2 + \theta^2 \mu \left[ \frac{E_{I/N}}{m_{I/N}} \right]^{\frac{1}{2}}, \tag{II-D}
\]

where \(m_I\) is the mass of the particles of beam I and \(m_N\) is the mass of the particles of beam N. Rewriting Eq. II-D, neglecting the \(\theta^2\) term (which will be shown to be negligible), and assuming \(m_I = m_N\),

\[
E_{\text{cm}} = \frac{1}{2} (\sqrt{E_I} - \sqrt{E_N})^2. \tag{II-E}
\]

If \(E_I\) and \(E_N\) are replaced with the variables \(E = (E_{I/N})^{\frac{1}{2}}\) and \(\Delta E = E_I - E_N\), then Eq. II-E can be approximated by

\[
E_{\text{cm}} \approx \frac{\Delta E^2}{4E}. \tag{II-F}
\]

The accuracy of this approximation has been considered\(^{(6)}\) and Eq. II-F is accurate to better than 0.1% over the energy range reported in this thesis.

In the specific case of the merged beams apparatus discussed here, beam I is composed of helium ions, He\(^+\), and beam N is composed of He\(^0\). The primary beam energies \(E_I\) and \(E_N\) are varied from 700 ev to 3 kev depending upon the desired \(E_{\text{cm}}\), and \(\theta\) has been measured to be less than 1/200 radian. The magnitude of the \(\theta\) dependent term of Eq. II-D is then

\[
\mu \theta^2 \left( \frac{E_{I/N}}{m_{I/N}} \right)^{\frac{1}{2}} < 0.02 \text{ ev}, \tag{II-G}
\]
which is less than 0.5% of the value of $E_{\text{cm}}$ reported in this thesis.

It is instructive to consider the energies which are required to obtain a given $E_{\text{cm}}$. For example if $E_N = 1$ keV and $E_I = 810$ ev, then $\Delta E = 190$ ev and from Eq. II-F, $E_{\text{cm}}$ is 5 ev. The ratio of $\Delta E$ to $E_{\text{cm}}$, nearly 40 in this case, is often referred to as the deamplification factor\(^{(7)}\). However the real advantage of the merged beams technique is in the excellent definition of $E_{\text{cm}}$. The beams I and N are actually formed from particles which have an energy distribution about their average energies $E_I$ and $E_N$. The variation in the primary beam energies causes a variation in $E_{\text{cm}}$, $\delta E_{\text{cm}}$, which from Eq. II-E is found to be

$$\frac{\delta E_{\text{cm}}}{E_{\text{cm}}} = 2 \frac{\delta E_I + \delta E_N}{|\Delta E|} \quad \text{II-H}$$

where $\delta E_I$ and $\delta E_N$ are the FWHM energy spread of beams I and N. For the specific case of the helium reaction to be studied, $\delta E_I$ and $\delta E_N$ have been measured to be less than 4 ev and 2 ev respectively (see Appendix I). Taking the previous example of $E_N = 1$ keV, $E_I = 810$ ev, and $E_{\text{cm}} = 5$ ev, $\delta E_{\text{cm}}$ from Eq. II-H is about 6% of $E_{\text{cm}}$. Such an energy definition is difficult to obtain with any other
low energy technique.

The variation of $\delta E_{cm}/E_{cm}$ as $E_{cm} \to 0$ can be obtained from Eq. II-F where $E_{cm} \propto \Delta E^2$ and Eq. II-F and II-G where $\delta E_{cm} \propto \Delta E$,

$$\frac{\delta E_{cm}}{E_{cm}} = \frac{1}{\sqrt{E_{cm}}} \quad \text{II-I}$$

As seen from Eq. II-I, as $E_{cm}$ decreases the percentage of variation in the collisional energy increases. However, cross sections with collisional energies $E_{cm}$ below 0.05 ev, and $\delta E_{cm}/E_{cm} < 50\%$ can be measured with the merged beams technique. The lower and upper limits on $E_{cm}$ are discussed in more detail by Geis$^8$ and by Smith$^9$. Generally, cross sections between 200 ev and 0.02 ev can be measured with the merged beams method.

Both beams used in the merged beams apparatus originate from plasma arc ion sources as shown in Figure II-A. The beams from the ion sources are focussed by a set of electrostatic lenses and are mass analyzed by two 60° oppositely bending magnets. The He$^+$ beam from ion source #1 passes through the charge exchange cell once it leaves the magnets where it is neutralized to form a neutral helium atom beam. The neutral beam from the cell passes through a series of apertures and differential pumping
LEGEND

α Arc source #1
β Einzel lenses
γ Deflection plates
δ Magnet
ε Aperture
θ Charge Exchange Cell
η Differential pumping aperture
ζ Arc Source #2
ι Merging magnet
λ Interaction Chamber
χ Detection Chamber
ψ Electrostatic Deflection System
φ Neutral Cup
γ Energy Analyzer and Electron Multiplier
τ Ion Cup
Δ Moveable Surface of known secondary electron emission for neutral calibration
stages which serve both to collimate the beam and to reduce the streaming of the charge exchange gas into the reaction chamber. A He\(^+\) beam, which is formed in arc source \#2, is then merged onto the neutral beam so that both beams move along together and may react to form He\(^+\) product. After both beams move through the interaction chamber, the ions and neutrals are separated electrostatically. Any product helium ions which may have been formed in the interaction chamber are deflected onto an electron multiplier. The current of the He\(^+\) beam is collected in a Faraday cup and the intensity of the He\(^0\) beam is monitored by measuring the secondary electron emission current on a surface of known secondary electron ejection coefficient\(^{10}\). Table II-B shows typical primary beam intensities and secondary electron ejection coefficients for the beam energies used during the experiment.

To determine an accurate cross section with the merged beam technique it is necessary to measure the fluxes of the two primary beams over the volume in which they interact to produce signal ions. The procedure used to do this is discussed in Chapter III. Also, the rate of production of product helium ions, \(S_m\), must be accurately measured.
### Table II-B
Primary Beam Intensities

<table>
<thead>
<tr>
<th>Neutral beam energy keV</th>
<th>Intensity (in μA assuming each atom has charge e)</th>
<th>Secondary electron coefficient γ used for neutral beam calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.6</td>
<td>1.15</td>
</tr>
<tr>
<td>1.5</td>
<td>0.16</td>
<td>1.08</td>
</tr>
<tr>
<td>1.0</td>
<td>0.09</td>
<td>0.96</td>
</tr>
<tr>
<td>0.9</td>
<td>0.08</td>
<td>0.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ion beam energy keV</th>
<th>Intensity in μA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>0.7</td>
<td>0.08</td>
</tr>
<tr>
<td>0.5</td>
<td>0.04</td>
</tr>
</tbody>
</table>
The accuracy of the determination of $S_m$ depends mainly upon the noise generated by the random nature of the background counts, and upon the counting time $T$. Assuming that the background count rate, $BG$, is Poisson distributed in time, then the variation in the determination of $S_m$, $\delta S_m$, is given by

$$\frac{\delta S_m}{S_m} \propto \frac{1}{S_m} (\frac{BG}{T})^{1/2}. \quad \text{II-J}$$

It can be seen that to minimize the counting time it is desirable to reduce the background count rate.

The background counts originate from three sources. The first source is associated with the neutral beam striking the back of the neutral Faraday cup. The exact mechanism by which the neutral beam produces background counts in the electron multiplier is unknown. However, this source of background was reduced more than an order of magnitude by placing thin aluminum sheets arranged in a honeycombed structure in the neutral Faraday cup, thereby changing the length to diameter ratio of the cup from 2 to an effective ratio of 30. The background from this source was on the order of $2 \times 10^3$ counts/sec.

The second source of background arises when fast neutral helium atoms of the neutral beam are ionized (stripped) by
collisions with residual gas in the interaction chamber. These ions have an energy at least 25 ev (ionization energy of helium) below the energy of the signal ions. This enables an energy analyzer, shown in Figure II-A, to reject these slower ions and allows the signal ions to pass onto the electron multiplier. The background from this source is thereby eliminated. However, at neutral energies of 3 keV and above, the resolution of the energy analyzer is insufficient to resolve ions formed through stripping from signal ions, and the background produced by these ions becomes a problem. Acceptable count rates were obtained for neutral energies of 3 keV by maintaining the interaction chamber pressure below 2x10^{-9} torr. The background contribution from stripping was about 2x10^5 counts/sec in the worst case and was negligible for neutral beam energies below 3 keV. The energy analyzer and vacuum chamber pressures are discussed in Appendixes I and II.

The largest source of background is produced by the ion beam. The mechanism for the production of this background is believed similar to that of the background from the neutral beam. Generally it was not possible to direct the ion beam into a Faraday cup during a cross section measurement, and a background count rate of 7x10^5
counts/sec was not unusual. However, even with these large count rates, cross section measurements were obtained with standard deviations on the order of 10% in 60 minutes or less.
CHAPTER III
DETERMINATION OF A CROSS SECTION

A cross section for a given reaction can be obtained with the merged beams technique from

$$\sigma = S \frac{V_I V_N}{V_I - V_N} \left[ \iiint J_I J_N \, dV \right]^{-1}, \quad III-A(11)$$

where $\sigma$ is the cross section for a given reaction, $S$ is the signal formed from the reaction in particles/sec, $V_I$ and $V_N$ are the velocities of the ion and neutral beams respectively, and $\iiint J_I J_N \, dV$ is the volume integral of the neutral and ion fluxes, $J_N$ and $J_I$, in particles$^2$/sec$^2$-cm. The signal, $S$, is measured by electrostatically deflecting the product ions into an electron multiplier, as shown in Figure III-A. An energy analyzer located immediately in front of the electron multiplier is used to reject ions formed from stripping of the neutral primary beam by collisions with background gases, as discussed in Appendix I. The product ions incident on the electron multiplier produce secondary electrons which are amplified by the electron multiplier to produce electrical pulses. These pulses are
FIGURE III-A: DIAGRAM OF DETECTION AND INTERACTION CHAMBERS

Merging Chamber

Interaction Chamber

Pressure \( \approx 1 \times 10^{-9} \text{ torr} \)

Pressure \( \approx 4 \times 10^{-8} \text{ torr} \)

Merging Magnet

Length Over Which Signal is Formed.

Detection Chamber

Pressure \( \approx 1 \times 10^{-9} \text{ torr} \)

Ion Beam

Signal Beam

Neutral Beam

Energy Analyzer

Neutral Cup

Beam Separation Deflection Plates

Calibrated Secondary Electron He\(^+\) Cup

Electron Multiplier

I_{He}^+

I_{He}^0

I_{signal}
fed into the support electronics as shown in Figure III-B. The signal lead and ground lead of the electron multiplier pass through a ferrite bead which acts as a common mode filter to remove most of the ground loop noise originating from radio frequency interference. A cable shaping network was added to the system to eliminate the effects of large voltage drifts in the linear DC amplifiers, and to avoid level shifts in the amplifiers due to "pulse pileup"\(^{(12)}\). This is accomplished by using the reflected wave from a shorted coaxial cable to offset any level shift.

The pulses from the multiplier, after being amplified and shaped, pass through a discriminator and are registered in one of two scalers. The gating is shown in Figure III-C, and is designed to eliminate background counts originating from the primary beams. The ion and neutral beams are chopped at 250 Hz with a 50% duty cycle, and 90° out of phase. If \( BG_I \) and \( BG_N \) are the background count rates from the ion and neutral beams, BG is the background count rate from the electron multiplier and associated electronics, and \( S_m \) is the signal count rate, then from Figure III-C scaler 1 measures \( T(BG_N + BG_I + BG) \) and scaler 2 measures \( T(S_m + BG_N + BG_I + BG) \), and the difference between the scalers gives \( TS_m \).
FIGURE III-B: SUPPORT ELECTRONICS

From Electron Multiplier

Common Mode Rejection Filter

x100

Cable Shaping Network

Discriminator Voltage Level 0.25 V

1 kHz Clock

To Beam Chopping Electronics

Scalar 1

Scalar 2

Printer
Periodically the positions of the ion and neutral beams in the counting sequence are interchanged as shown in Figure III-D. This technique eliminates any possible systematic errors in the measured signal due to intensity variations in the primary beams caused by the beam chopping. For example, assume that the intensity of the neutral beam is modulated as shown in Figure III-D. When the neutral beam precedes the ion beam then the difference of scalers 1 and 2 is $T(S_m + [BG_{N1} - BG_{N2}])$ where $BG_{N1}$ is the average background rate of the neutral beam measured for the first counting period of the neutral beam's operation, and $BG_{N2}$ is the average background count rate for the second counting period of the neutral beam. When the position of the beams is interchanged the difference of scalers 1 and 2 is $T(S_m - [BG_{N1} - BG_{N2}])$. By adding the differences of the scalers for the two beam positions, the effect of the neutral beam's variation cancels out, giving only the signal count. It should be pointed out however, that this operation will not eliminate any cross talk between beam choppers. If for example, the neutral beam chopper somehow modulated the intensity of the ion beam, then a systematic error in the measured signal would exist. This possible source of error has been examined and is discussed in Chapter IV.
FIGURE III-D(i): COUNTING SEQUENCE (NEUTRAL BEAM PRECEDES ION BEAM)

FIGURE III-D(ii): COUNTING SEQUENCE (ION BEAM PRECEDES NEUTRAL BEAM)
Three corrections must be made to the measured signal \( S_m \) in order to determine the true cross section. Although the primary beams are chopped in phase with the counting periods, the transit times of the beams through the apparatus cause the beams and the signal to appear in the detection chamber slightly out of phase with counting sequence. The background counts from the ion and neutral beams still subtract out of the difference in scalers 1 and 2; however, some of the signal counts appear in scaler 1 during count period 3. Allowance is made for the time displaced by

\[
S_T = S_m \cdot \frac{T_P}{T_P - t_I - t_N} \quad \text{III-B}
\]

where \( S_T \) is the actual signal arriving at the input to the scaler. \( T_P \) is the time of one counting period, and \( t_I \) and \( t_N \) are the transit times of the ion and neutral beams respectively from the beam choppers to the detection chamber.

Eq. III-B, which is derived in Appendix III, represents an adjustment of 1 to 2% of the measured signal.

The second and third corrections arise due to the counting efficiency of the electron multiplier and the dead time of the support electronics. Calibration of the electron multiplier was accomplished by directing a low intensity He\(^+\)
beam through the energy analyzer onto the electron multiplier. A measured count rate \( R_m \) was then obtained. The same ion beam was then deflected into a Faraday cup, where the current was measured with a Keithley 610C electrometer. Dividing this current by the electronic charge \( e \) the true count rate \( R_t \) is obtained. The measured count rate and the true count rate are related by

\[
R_t = \frac{R_m}{F(1 - T_D R_m)} \tag{III-C(13)}
\]

where \( F \) is the detection efficiency of the \( \text{He}^+ \) ions, and \( T_D \) is the dead time of the electronics, defined as the length of time after receiving a pulse that the counting system is incapable of recording another pulse. Inverting the above equation,

\[
\frac{1}{R_t} = F\left(\frac{1}{R_m}\right) - FT_D \tag{III-D}
\]

is obtained. By determining \( R_t \) and \( R_m \) for a number of different beam currents, then \( F \) can be obtained from the slope of a graph of \( 1/R_t \) vs \( 1/R_m \). \( T_D \) can also be obtained from the intercept on the axis of \( 1/R_m \). An example graph of \( 1/R_t \) vs \( 1/R_m \) is shown in Figure III-E. Using a least squares fit to a straight line a detection efficiency of
FIGURE III-E: RECIPROCAL OF TRUE COUNT RATE VS. RECIPROCAL OF MEASURED COUNT RATE

\( \frac{1}{R_t} \times 10^{-6} \text{ sec/count} \)

\( \frac{1}{R_m} \times 10^{-6} \text{ sec/count} \)
72 ± 2%* was obtained with a dead time of 38 ± 10 nsec.
The signal corrected for detection efficiency and dead
time, $S_A$, is

$$S_A = \frac{4}{F}[S_M + 8BG_NBG_I^T_D], \quad \text{III-E}$$

where $BG_N$ and $BG_I$ are the number of background counts
arriving in scaler 1 per second due to the neutral and
ion beams respectively, and $S_M$ is the number of signal
counts per second as determined by the numerical differ-
ence of scalars 1 and 2. This equation was obtained from
Eq. III-C, however, the derivation is slightly involved
due to the chopping of the primary beams. Appendix IV
gives a detailed derivation. Typically, the dead time
correction amounts to a 1 to 5% adjustment of the measured
signal.

Considering the multiplier efficiency, beam chopping,
flight time and dead time adjustments the actual signal
arriving at the electron multiplier per second $S$ is

$$S = \frac{4}{F}[S_M + 8T_DBG_NBG_I] [\frac{T}{T - T_N - T_I}], \quad \text{III-F}$$

$S$ varies from $5 \times 10^3$ to 200 counts/sec with statistical

* All errors are given as ± one standard deviation unless
otherwise noted.
fluctuations of 1 to 10% depending principally on the primary beam intensities, the cross section, and the number of background counts.

The velocities of the ion and neutral beams were obtained from the measured energy of the beams assuming that the neutral beam has the same velocity as the ion beam from which it was formed. The energy of the primary beams was obtained from measurements with the energy analyzer discussed in Appendix I.

The beam overlap can be written as

\[ \xi = \int_{z_1}^{z_2} \int_{A} J_I J_N \, dz \, A \int_{A} J_I J_N \, dx \, dy, \]

where \( J_I, J_N \) are the fluxes of the ion and neutral beams, \( z_1 \) and \( z_2 \) are the positions along the primary beam axis (z axis) between which the ion and neutral beams interact, and \( A \) is the area in a plane perpendicular to the z axis over which a two dimensional overlap is obtained. To obtain the exact evaluation of \( \xi \), the two dimensional overlap, \( \int_{A} \int_{A} J_I J_N \, dx \, dy \), must be taken continuously between the points \( z_1 \) and \( z_2 \). Due to the impracticality of obtaining such an integral, Eq. III-G can be approximated by taking the two dimensional overlap at several positions along the beam path and then fitting the two dimensional overlap to a
functional form of \( z \) which can be easily integrated between \( z_1 \) and \( z_2 \). In the present experiment the two dimensional overlap was measured at four positions along the merged beams axis and the functional form consisted of straight lines between the points as shown in Figure III-F. The area under the curve was then obtained by a numerical integration technique. Since the overlap of the two beams is consistently larger at the beginning of the interaction region than at the end, the beam flags at the beginning of the interaction region were spaced closer together to obtain a more accurate overlap measurement. If the functional form shown in Figure III-F is replaced by a least squares quadratic, the value of typical overlaps used to determine cross sections changes by less than 5%.

The two dimensional overlaps are obtained by moving beam scanner segments through the merged ion and neutral beams as shown in Figure III-G and Figure III-H. Each of the four scanners has nine pinhole apertures evenly separated at increasing radial distance from the scanner shaft. As the shaft is rotated, these holes move along different circular paths transverse to the beam axis. The neutral and ion fluxes passing through the pinholes are electro-
FIGURE III-E: TWO DIMENSIONAL OVERLAP VS. DISTANCE Z
statically separated and the ion current is collected in a Faraday cup while the neutral flux is monitored by the secondary electron emission from a calibrated metal surface. The signals from the ion and neutral beams are amplified, filtered, multiplied and integrated as shown in Figure III-I to obtain a voltage \( V_o \) which is related to the two dimensional overlap by

\[
\int_A J_I J_N dA = \frac{Sr\omega RC}{\gamma a^2 G} V_o, \quad \text{III-H (14)}
\]

where \( \gamma \) is the secondary electron emission of the neutral detector, \( S \) is the radial spacing between adjacent holes on the beam scanner, \( r \) is the average radius from the pinholes to the center of the beam scanner shaft, \( a \) is the area of the pinholes, \( \omega \) is the angular velocity of the beam scanner, \( R, C, G \), are circuit parameters and \( V_o \) is the voltage output from the integrator.

To avoid the necessity of calculating all parameters required for Eq. III-H, a "calibration" scan is made in which one of the beams is blocked prior to the merging magnet and its input to the circuit in Figure III-I is replaced with a known constant current. Under these conditions the output of the integration \( V'_o \) is given by

\[
\int_A J_I dA = \frac{Sr\omega RC.V'_o}{\gamma aG}, \quad \text{III-I}
\]
Figure III-1: Overlap Circuitry

\[ V_0 = \int \left[ kV_{kV,xy} \right] dt \]

Multiplier

Low Pass Filter

\[ V_x = I_2 R_2 \]

Low Pass Filter

\[ V_Y = I_1 R_1 \]

\[ I_2 \]

\[ I_1 \]
where \( I \) is the known current which, for example, replaced the neutral beam. Since \( I = \int J \, dA \) where \( I \) is the current of the primary ion beam, then from Eq. III-H and Eq. III-I

\[
\int_A J_1 J_N \, dA = \frac{I I^*}{\gamma a} \frac{O_o}{V_0} \quad \text{III-J(15,26)}
\]

The only quantities which must be known in order to calculate the overlap are the pinhole area \( A \) and \( \gamma \). The radii of the scanner pinholes were measured with a calibrated microscope from which area, \( a \), was obtained. The secondary electron emission coefficient \( \gamma \), for the neutral beam was assumed to be equal to that for an ion beam of the same energy. This equality has been experimentally verified for the same surface used in this experiment with neutrals and ions of helium from 900 ev to 6 keV(16).

The limits of the overlap integral \( z_1 \) and \( z_2 \) are defined by the merging magnet and the electrostatic deflection system in the detection chamber. The exact position of \( z_2 \) is relatively unimportant. This is because the overlap of the merged beams in this area is small since they are diverging and their flux densities are decreasing with increasing \( z \). The same is not true for the position of \( z_1 \), since the overlap is large at the beginning of the
interaction region. To determine the position of $z_1$ the
effect of the fringing field of the merging magnet on the
signal ions formed during merging must be taken into con-
sideration. Signal ions formed near the merging magnet
are deflected by its fringing field and, therefore, miss
the electron multiplier.

At positions farther into the interaction region the
effect of the merging magnet is diminished and signal ions
formed at these positions can be counted with the electron
multiplier. The position along the merged beam path where
the fringing field of the magnet no longer affects the
collection of signal ions can be estimated by performing
a simple trajectory calculation if the fringing field of
the merging magnet is known. The relevant equation for
describing the fringing field of the magnet is derived in
Appendix V. Figure III-J shows a comparison of the mea-
sured field with the calculated field. The angle $\theta$ through
which the signal ion is deflected by the fringing field $B$
is given by

$$ \theta \approx -\int_{-\infty}^{z_1} \frac{B(x)e}{mv} \, dx = -\int_{-\infty}^{z_1} \frac{1.35}{(x+1)(x^2+5)} \, \frac{B_0 e}{mv}, \quad \text{III-K} $$

where $B_0$ is the magnetic field between the merging magnet's
poles and $e/mv$ is the charge to momentum ratio for $\text{He}^+$ in cgs.
FIGURE III-J: NORMALIZED FIELD & CALCULATED FIELD vs. DISTANCE

\[ \frac{B}{B_0} = \frac{1.35B_0}{(x^2 + 1)(x^2 + 5)^{3/2}} \]

Distance from Pole Face → in inches

Measured Value

Calculation for "Far" Field
From geometrical considerations the maximum angle through which a detected signal ion can be deflected and still strike the multiplier is $1/150$ radian. By carrying out the integration $z_1$ was found to be $2.5 \pm 0.7$ inches from the edges of the pole faces of the merging magnet.
CHAPTER IV
CHECKS ON SPURIOUS EFFECTS

The data presented in this dissertation represent the first measurements obtained from the merged beams apparatus. Therefore, this entire chapter is devoted to describing checks made on the apparatus to ensure that spurious effects did not adversely affect the cross section measurements. From Chapter III, the cross section is defined by

\[ \sigma = S \frac{V_{IN}}{|V_I - V_N|} \left[ \int \int \int J_I J_N dV \right]^{-1}, \]  

where the parameters are as defined previously. Checks for each variable present in Eq. IV-A will be described.

The signal \( S \), which is obtained from

\[ S = \frac{4}{F} [S_M + 8T_D B G N I] \frac{T_P}{T_P - (t_I^+ + t_N)}, \]  

as discussed in Chapter III, is determined from several measured parameters. The measured count rate, \( S_M \), which is the difference between the count rates of scalars 1 and 2, can be affected by the electronics.
Since the apparatus has a great deal of wiring from the instrumentation racks leading to the vacuum chambers, there was concern that ground loop currents could exist. If these currents were in phase with the beam chopping, spurious signals could occur due to voltage level shifts between the electron multiplier and the amplifier and discriminator. Cross modulation of the beams could also occur, as shown in Figure IV-A, where, in this case due to ground loop currents, the ion beam is slightly modulated by the chopping of the neutral beam. Further, as shown in Appendix III the counting periods must satisfy the equation

\[ \frac{T}{P_1} + \frac{T}{P_2} - 2\frac{T}{P_2} = 0, \]  

for the background counts from the neutral and ion beams to subtract out of \( S_M \). These considerations were checked by running only one beam with both beam choppers in operation. This made it possible to operate the apparatus with all the ground loop currents which are present during a cross section measurement, but without any product formation. Therefore, any signal produced would be due to a ground loop current or to irregular counting periods.
FIGURE IV-A: EXAMPLE OF CROSS MODULATION OF THE BEAMS

Ion Beam 0
Intensity

Neutral Beam 0

Time →

Scalar 1 0 1

Scalar 2 0 1
It was found that no such effect existed, to within one part in $10^4$ of the total background, which represents less than 1% of the measured signal during a cross section measurement.

The detection efficiency of the electron multiplier and counting system, $F$, was measured several times over the period in which cross section measurements were taken, and was found to vary from 74% to 70%. The efficiency was found to be independent of the counting rate from $5 \times 10^6$ counts/sec to $5 \times 10^4$ counts/sec to within the accuracy of the technique of ± 3%. The counting rates varied from $1.5 \times 10^5$ counts/sec to $2 \times 10^4$ counts/sec for a given cross section measurement.

The dead time $T_D$, which was determined solely by the electronics of the discriminator, was measured three separate ways. The first method was the graphic technique described in Chapter III. The second technique was to send two pulses into the discriminator. If the time between these pulses is long compared to the dead time of the discriminator then both pulses can be monitored on the output of the discriminator. As the time between the pulses, $T$, was reduced, some value of $T$ was reached at which the discriminator could not distinguish both pulses.
and only one pulse appeared on the discriminator output. This value of \( T \) was then assigned to be the dead time.

The third technique was to run both beams through the apparatus as if to measure a cross section, but no voltages were applied to the deflection system at the entrance to the detection chamber. Therefore, the signal ions were not deflected onto the electron multiplier and only background from the ion and neutral beams were counted. By setting the signal \( S \) of Eq. IV-B equal to zero and solving for \( T_D \),

\[
T_D = \frac{S_m}{8BG_BG_I} \quad \text{IV-D}
\]

Then by measuring \( S_m', BG_N', \text{ and } BG_I \), \( T_D \) can be obtained from Eq. IV-D. Figure IV-B shows the effect of dead time on the measured signal \( S_m \) when no signal ions are produced. The calculated signal \( S_m \) is also shown for comparison. The equations used to obtain the calculated values of \( S_m \) as a function of dead time were obtained from Fenyves\(^{(17)}\).

The first technique gave a dead time of 38 nsec, while the second and third techniques gave 30 and 20 nsec respectively. For calculations of cross sections \( T_D \) was assumed to be 30 \( \pm \) 10 nsec. This uncertainty in \( T_D \) produces from 1 to 5% uncertainty in the measured cross section.
FIGURE IV-B: NEGATIVE SIGNAL vs. DEAD TIME

Negative Signal in Counts per Second

Dead Time, μsec.

Calculated
The determination of $T_p$, $t_I$, and $t_N$ is of little importance since they represent about a 1 to 2% correction on the signal; however, these quantities were measured with a 1710A Hewlett Packard oscilloscope.

To determine a cross section it is imperative that all of the ions formed from the reaction be collected. Several experimenters have measured the differential elastic cross section and have found that, although the product ions formed from the reaction of interest are highly peaked in the forward direction, a significant amount are scattered several degrees from the forward direction in the center of mass reference frame (18,19). For an electron multiplier 3.8 cm (20) in diameter and 150 cm away from the beginning of the interaction region, a product ion can be scattered up to $0.78^\circ$ and still be registered. This laboratory scattering angle can be translated into a center of mass scattering angle by

$$\theta_{cm} = 0.78^\circ \left( \frac{E_N}{E_{cm}} \right)^{\frac{1}{3}},$$

where $E_N$ is the energy of the neutral beam and $E_{cm}$ is the center of mass energy. Of the measured cross sections the smallest acceptance angle, $\theta_{cm}$, was $3^\circ$, for $E_{cm} = 200$ ev and $E_N = 3$ keV. Since the angular distribution of reaction
products is nearly energy independent \(^{(21)}\), the cross section measurement at \(E_{\text{cm}} = 200\) eV represents the worst case condition. From elastic differential scattering data of \(\text{He}^+\) on \(\text{He}^0\) at 200 eV, an estimated cross section for product ions to be scattered greater than \(3^\circ\) is 1 \(\text{A}^2\). With a total reaction cross section of 10 \(\text{A}^2\) the collection efficiency of the apparatus is 90%. The large collection efficiency is borne out by deflecting the product ions across the electron multiplier with the deflection system at the beginning of the detection chamber. If the scattering cone of the product ions is small compared to the electron multiplier, then a graph of signal vs deflection voltage will have a plateau as the cone of product ions is deflected across the multiplier's active area, and will have steep edges as the cone is deflected off the multiplier, as shown in Figure IV-C. For a comparison, Figure IV-D shows the number of counts measured by the electron multiplier as a function of deflection voltage for a sample ion beam of 0.1" diameter.

As discussed by Bayfield \(^{(22)}\), excited states of the primary neutral beam can cause a spurious signal, due to their large cross section for reaction with the primary ion beam. To minimize the possible effects of excited states, the neutral helium beam was formed from resonant charge
Normalized signal
≈ 1.2\times10^3 \text{ counts/sec}

Estimated variation

FIGURE IV-C: SIGNAL VS. DEFLECTION VOLTAGE
exchange of a fast ion beam in a gas cell containing helium. The pressure in the cell was regulated to make the gas a thick target to charge exchange, which has been shown to minimize the formation of excited states\(^{23}\). Under these conditions an upper limit on the two metastable states of helium has been established, less than two parts in \(10^3\). Muller et al\(^{24}\) have shown that more energetic excited states of He (1s, \(n \geq 5\)) are on the order of one part in \(10^4\) or less. Further, any highly excited states, He (1s, \(n \geq 29\))\(^{25}\) which might exist in the neutral beam, are eliminated by field ionization with a set of electrostatic plates just ahead of the merging magnet.

The possibility of excited states in the neutral helium beam was checked in several ways. The cross section for the reaction

\[
\text{He}^0 + \text{H}_2^+ \rightarrow \text{He}^+ + \text{H}_2
\]

was measured. This reaction is energetically impossible below 9 eV if the primary He\(^0\) is in the ground state. However, the reaction is energetically possible if the He\(^0\) is in an excited state. The cross section for this reaction was measured to be \(0.23 \pm 0.3 \, \text{mb}^{2}\), which is effectively zero when compared to the cross sections measured for the resonant charge exchange. The possible effects of excited states
were also studied by measuring the resonant charge exchange cross section as a function of neutral beam energy, with the center of mass collisional energy held constant at 31 ev. The fraction of excited states of the neutral beam is predicted to increase with the neutral beam energy\(^{(26)}\). If these states contribute to the measured cross section, then the cross section would increase with the neutral beam energy. As shown in Figure IV-E no such effect occurred to within the accuracy of the measurements.

The velocities of the ion and neutral beams, \(V_I\) and \(V_N\), were determined from the energy of the ions used to form the beams, as measured using the energy analyzer. Two techniques which are discussed in Appendix I, were used to obtain the energy of these ions, both giving the same results. To check that the velocities could be consistently determined two cross section measurements were made with the same center of mass collisional energy and the same neutral beam velocity but with different ion beam velocities. The cross sections were found to be equal to within the estimated uncertainty.

The technique used to measure the overlap of the beams was checked in two ways. The first method was to measure the overlap of only a single beam. By substituting a known
Table IV-H
Experimental Uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty in determining parameters</th>
<th>Resultant uncertainty in cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured signal, $S_m$</td>
<td>1 - 13%</td>
<td>1 - 13%</td>
</tr>
<tr>
<td>Electron multiplier efficiency, $F$</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Ion beam background, $B_G^I$</td>
<td>1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Neutral beam background, $B_G^N$</td>
<td>1%</td>
<td>≈ 0.1%</td>
</tr>
<tr>
<td>Dead time, $T_D$</td>
<td>30%</td>
<td>1 - 10%</td>
</tr>
<tr>
<td>Counting period, $T_p$</td>
<td>5%</td>
<td>≈ 0.1%</td>
</tr>
<tr>
<td>Ion beam transit time, $t_I$</td>
<td>10%</td>
<td>≈ 0.1%</td>
</tr>
<tr>
<td>Neutral beam transit time, $t_N$</td>
<td>10%</td>
<td>≈ 0.1%</td>
</tr>
<tr>
<td>Velocity factor, $V_I/V_N/(V_I-V_N)$</td>
<td>1 - 5%</td>
<td>1 - 5%</td>
</tr>
<tr>
<td>Overlap length, $z_1$, $z_2$</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>Secondary electron coefficient, $\delta_o$</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Two dimensional overlap, $\int_A J_I J_N dA$</td>
<td>7%</td>
<td>7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty in determining parameters</th>
<th>Resultant uncertainty in $E_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion beam energy, $E_I$</td>
<td>0.1 - 0.7%</td>
<td>0.5 - 7%</td>
</tr>
<tr>
<td>Neutral beam energy, $E_N$</td>
<td>0.1 - 0.3%</td>
<td>0.6 - 2%</td>
</tr>
</tbody>
</table>
constant current $K$ for one of the primary beams, the two dimensional overlap becomes

$$\int_A K J_I \, dA = K \int_A J_I \, dA = K I,$$

where $J_I$ is the flux of the ion beam, $A$ is the area of the overlap and $I$ is the total ion beam current. The single beam overlaps were measured for each of the four beam flags, using ion beams of different shapes and intensities. The total ion beam current as measured by the single overlap technique agreed with the actual current collected in a Faraday cup to within 3% for all four beam flags\(^{(27)}\). The second check was made by taking several cross section measurements with different overlaps. Figure IV-F shows that the cross section is independent of the measured overlap.

As discussed in Chapter III, the neutral beam flux $J_N$ must be measured in the determination of an overlap integral. This was done by assuming that the secondary electron ejection coefficient $\gamma_+$ for fast neutral He\(^0\) atoms is the same for He\(^+\) atoms with identical velocities. Under this assumption, the neutral beam intensity $I_N$ in particles/sec is given by

$$I_N = \frac{I_e}{\gamma_+},$$
FIGURE IV-F: NORMALIZED CROSS SECTION vs. INTEGRAL

\[ \int_{1}^{7} J_N d\nu \text{ in } \frac{\text{particles}^2}{\text{sec}^2\text{cm}} \times 10^{26} \]
where \( I_e \) is the secondary electron current ejected by the neutral beam and \( \gamma^+ \) is the secondary electron ejection coefficient for \( \text{He}^+ \) ions. This assumption was verified in a previous experiment \(^{(28)}\), in which the secondary electron ejection coefficients, for ions and for neutrals, were found to be equal to within 3\% for impact energies from 900 eV to 4 keV. Other investigators have found similar results \(^{(29,30)}\).

The overlap of the two primary beams used to determine a cross section was taken with the beams running in a DC mode; however, the signal was measured with the beams chopped. There was concern that position of the beams with respect to each other was different for the DC and the chopped modes. The possibility of this occurring was checked by taking an overlap with the beams in the chopped mode. This required that low pass filters be placed in the overlap circuitry as shown in Figure III-J to filter out the high frequency components of the beam chopping. It was found that the overlap with the beams on DC was in agreement with the overlap obtained with the beam chopped, to within 10\%. The difficulty with the overlap obtained for the beams run in a chopped mode is that the output voltage from the overlap electronics is reduced by a factor
of four which can significantly reduce the accuracy of the overlap, since the electronic noise is the same for both techniques.

Several miscellaneous consistency checks were made on the apparatus. The cross section should be independent of the beam chopping frequency. Normally the beams were chopped at 250 Hz, and no measurable effect on the cross section was observed by increasing the chopping frequency first to 500 Hz and then to 1000 Hz.

Since the charge exchange reaction is resonant, the signal ions should have the same energy as the particles comprising the neutral beam. A comparison of the energy of the signal ions with the energy of the primary ions used to form the neutral beam was obtained by measuring the intensities of each as a function of energy analyzer voltage as shown in Figure IV-G.

The accuracy of the measured cross sections depends upon uncertainties in the experimentally measured parameters used in Eqs. IV-A and IV-B. The parameters of Eq. IV-B used to obtain the signal, S, have been previously discussed. The variation in the cross section due to the uncertainties in the determination of these parameters is displayed in table IV-H. The second term of Eq. IV-A,
FIGURE IV-G: SIGNAL vs. VOLTAGE ON ENERGY ANALYZER & INTENSITY OF IONS USED TO FORM NEUTRAL BEAM vs. VOLTAGE ON ENERGY ANALYZER

- Signal Corrected for Dead Time
- Intensity of Ions used to form neutral beam vs. Voltage on Energy Analyzer

Voltage on Energy Analyzer in keV →
\( V_{IN} / |V_I - V_N| \), is determined solely from the energies of the ion and neutral beams, as measured by the energy analyzer. The energy analyzer can determine the relative energy of a given beam to within 0.1\% as discussed in Appendix I. However, the absolute energy measurements must rely on a voltage standard. A recently acquired Keithley 168 Digital Voltmeter, with an estimated error of \( \pm 1\% \), contributes only \( \pm 0.5\% \) variation to the velocity term. The largest sources of uncertainty come from the 0.1\% determination of the relative energy of the beams and the natural energy spectrum of the ion and neutral beams of 8 eV and 4 eV FWHM. The variation in the determination of the velocity factor, \( \delta (V_{IN} / |V_I - V_N|) \), can be calculated from

\[
\delta \frac{V_{IN}}{|V_I - V_N|} = \frac{\delta V_{IN}}{|V_I - V_N|} \cdot \frac{dV_I}{dE_I} \cdot \delta E_I + \frac{\delta V_{IN}}{|V_I - V_N|} \cdot \frac{dV_N}{dE_N} \cdot \delta E_N'
\]

where \( \delta E_I \) and \( \delta E_N \) are the uncertainties in the measurements of \( E_I \) and \( E_N \) respectively, and are given by

\[
\delta E_I = 4 + E_I (1 \times 10^{-3}) \quad \text{IV-I}
\]

and

\[
\delta E_N = 2 + E_N (1 \times 10^{-3}) \quad \text{IV-J}
\]
Taking the derivatives of Eq. IV-H and solving in terms of $E_N$ and $E_I$,

$$\frac{\delta V_{IN}}{|V_I - V_N|} = \frac{E_N}{E_{cm}} \cdot \frac{\delta E_I}{E_I} + \frac{E_I}{E_{cm}} \cdot \frac{\delta E_N}{E_N} \cdot \frac{1}{2^{3/2}}$$

is obtained. The uncertainties, as determined by Eq. IV-K, vary between 5% for the cross section obtained at 5 eV to less than 1% for the cross section obtained at 200 eV.

There are other parameters not considered in this thesis which can contribute to the variation of $V_{IN}/|V_I - V_N|$, like beam misalignment and ion and neutral beam divergences. In the energy range over which the cross section measurements were made the contribution to the cross section variation from these parameters is negligible.  

The sources of error in determining an overlap,

$$\int_{I_N} \int_{J} dV$$

are first of all the errors associated with the beam flags and overlap support electronics, which have been estimated by Nitz et al. to be ± 7%. The assumption that the secondary electron emission is the same for neutrals and ions is estimated to cause an error no greater than ± 3% on the basis of previous data.  

The length of the interaction region of the two beams, defined by $z_1$ and $z_2$ as discussed in Chapter III is 150 cm with an
estimated uncertainty of ± 3 cm, which is determined primarily by the fringing field of the merging magnet, where the overlap is greatest. Finally the current measurements necessary for the absolute determination of \( J_N, J_I \), and the electron multiplier efficiency, \( F \), were calibrated against a Cary 401 Vibrating Reed Electrometer to within an estimated uncertainty of ± 3%.

From the above considerations, the total RMS systematic error which is attributed to the uncertainty in measurements of dead time, neutral beam intensities, electron multiplier efficiency, overlap length, and absolute current varies from 4% to 10%. The total random RMS uncertainty, which is calculated from the variation in the determination of \( S, \frac{v_I v_N}{v_I - v_N} \) and the overlap, varies from 8% to 12%. The possible systematic error due to the scattering of signal ions outside the active area of the electron multiplier has been neglected in this error analysis, since there is insufficient information to make a correction for these ions; however, as previously discussed, the maximum error due to this effect is less than 10%.

The accuracy of the determination of the center of mass energy \( E_{cm} \), as discussed in Chapter II, varies from
9% for $E_{cm} = 5$ eV to less than 1% for $E_{cm} = 200$ eV.
CHAPTER V
RESULTS AND DISCUSSION

The measured cross sections, along with the total RMS uncertainty, are shown in Table V-A. Figure V-B shows the comparison of the present data with available cross sections as measured by Mahadevan et al\textsuperscript{(31)} and by Nagy et al\textsuperscript{(32)}. Theoretically predicted cross sections of Rapp and Francis\textsuperscript{(33)} and Massey and Gilbody\textsuperscript{(34)} are shown for comparison.

There is a subtle difference between the previously measured cross sections of Mahadevan and Nagy and the other information shown in Figure V-B. The measurements of Mahadevan and Nagy represent the cross section for the neutralization of helium ions for both resonant and non-resonant collisions. However, the data presented in this thesis and the theoretically predicted cross sections are obtained for only the resonant charge exchange reaction. Comparing the resonant charge exchange cross section to the total charge exchange cross section is valid, since from data of Dworesky et al\textsuperscript{(35)} and de Heer et al\textsuperscript{(36)} nonresonant collisions are expected to represent less

-61-
<table>
<thead>
<tr>
<th>$E_{cm}$, ev</th>
<th>Percentage Error in $E_{cm}$</th>
<th>$\sigma$, $\sigma^2$</th>
<th>Percentage Error in $\sigma$</th>
<th>$E_I$, keV</th>
<th>$E_N$, keV</th>
</tr>
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<tr>
<td>4.6</td>
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<td>21.6</td>
<td>15</td>
<td>0.735</td>
<td>0.908</td>
</tr>
<tr>
<td>7.0</td>
<td>7.2</td>
<td>11.9</td>
<td>12</td>
<td>0.785</td>
<td>1.008</td>
</tr>
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<td>14.9</td>
<td>4.2</td>
<td>13.3</td>
<td>9</td>
<td>1.115</td>
<td>1.509</td>
</tr>
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<td>29.4</td>
<td>3.2</td>
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<td>9</td>
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<td>1.509</td>
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<td>30.2</td>
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<td>12</td>
<td>0.575</td>
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<td>14</td>
<td>1.789</td>
<td>2.512</td>
</tr>
<tr>
<td>30.7</td>
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<td>12.7</td>
<td>6</td>
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<td>3.014</td>
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<td>31.1</td>
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<td>10</td>
<td>2.185</td>
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<td>48.8</td>
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<td>9</td>
<td>0.840</td>
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<td>99.4</td>
<td>1.6</td>
<td>7.7</td>
<td>7</td>
<td>1.665</td>
<td>3.014</td>
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<tr>
<td>198.3</td>
<td>1.2</td>
<td>9.2</td>
<td>7</td>
<td>1.215</td>
<td>3.014</td>
</tr>
</tbody>
</table>
FIGURE V-B: (CROSS SECTION) $\frac{1}{2}$ vs. $E_{cm}$

- $\text{RP}^{(33)}$
- $\text{MG}^{(34)}$
- $\text{Mahadevan}^{(31)}$
- $\text{Nagy}^{(32)}$

- Present Experiment
- Brackets Indicate 90% Confidence Limits

$E_{cm}$ in eV
FIGURE V-C: DIFFERENTIAL SCATTERING CROSS SECTION vs.
ANGLE FOR $E_{cm} = 200$ ev

$\frac{dI}{d\theta}$

in

$\frac{cm^2}{sterad.}$

Merged Beam
Apparatus Acceptance
Angle (Worst Case)

Nagy's Acceptance Angle

Scattering Angle for C.M. system in degrees
than 1% of the total charge exchange cross section.

Evaluation of the data of Mahadevan and Nagy hinges on an understanding of the techniques they used. Both experimenters used the ion beam attenuation technique in which a beam of He\(^+\) is passed through a gas cell of He\(^0\). As the ion beam moves through the cell some of the ions in the beam suffer elastic scattering and charge exchange collisions with the He\(^0\) gas of number density \( n \) (particles per \( \text{cm}^3 \)). The current \( I(x) \) in the ion beam after it passed a distance \( x \) cm in the gas cell is given by

\[
I(x) = I_0 e^{(\sigma_c + \sigma_s)xn}, \tag{V-A}
\]

where \( \sigma_s \) and \( \sigma_c \) are the elastic scattering and charge exchange cross sections respectively in \( \text{cm}^2/\text{particle} \) and \( I_0 \) is the current entering the gas cell. Generally the assumption is made that the elastic scattering cross section is small compared to the charge exchange cross section, i.e., \( \sigma_c \gg \sigma_s \), and Eq. V-A is used to obtain the cross section \( \sigma_c \):

\[
\sigma_c \approx \frac{1}{xn} \ln \frac{I(x)}{I_0}. \tag{V-B}
\]

The extent to which \( \sigma_s \) can be ignored depends, among other parameters, upon the geometry of the gas cell used in the
measurements. From differential elastic scattering data\textsuperscript{(37)} for He\textsuperscript{+} on He\textsuperscript{0} and a knowledge of the geometry of the gas cell used to obtain the data of Nagy, it can be seen that the published cross section could be as much as a factor of two too large, as in Figure V-B. In fact, because of elastic scattering, the data for the cross sections shown in Table V-A between 200 ev and 2 keV should be considered to be an upper limit. Figure V-C shows the differential elastic scattering data of He\textsuperscript{+} on He\textsuperscript{0} at 200 ev (center of mass collisional energy). The acceptance angle for the collection of I(x) in Nagy's apparatus and the acceptance angle for signal ions on the merged beams machine are also shown in Figure V-C.

Mahadevan used a slight variation on the ion beam attenuation technique to obtain cross section measurements. Grids mounted in the gas cell were used to collect slow ion current produced when fast ions charge exchange with the thermal gas in the cell. The slow ion current I\textsubscript{Slow} is given by

\[ I_{\text{Slow}} = I_0 (1 - e^{-N x \sigma_c}). \]  \hspace{1cm} \text{V-C}

From Eq. V-A and V-C the cross section was then obtained from

\[ \sigma_c = \frac{1}{N x} \ln [1 + \frac{I_{\text{Slow}}}{I(x)}]. \]  \hspace{1cm} \text{V-D}
Special care was taken to collect all the ions of $I(x)$, even those scattered several tens of degrees, making good the assumption that $\sigma_c \gg \sigma_s$. Using this technique Mahadevan estimates the error in the measured cross sections to be ± 20%.

The majority of theoretical calculations of resonant charge exchange cross sections are made under two assumptions. The first assumption is that the paths followed by the colliding particles are straight, i.e., only small angle scattering occurs during collisions. Secondly, the classical velocity of the electrons about the colliding atoms is large compared with the collisional velocity. This assumption makes it possible to separate the electronic and nuclear wave functions. The velocity range over which these assumptions are valid is often referred to as the "intermediate" velocity range. The upper limit on the velocity, which is determined on the basis of the validity of the second assumption, is on the order of $10^8$ cm/sec. This velocity represents a collisional energy of about 10 keV for $\text{He}^+$ on $\text{He}^0$. The lower limit on the collisional velocity depends upon the characteristics of the colliding atoms. In the case of $\text{He}^+$ on $\text{He}^0$ it is on the order of $10^5$ cm/sec or 0.01 eV$^{(38)}$. A brief description of the
considerations used to obtain theoretical cross sections in this velocity range is given below.

The charge exchange process in the "intermediate" range can be thought of as a two potential well problem. One well represents the neutral atom and contains an electron, the other well represents the atomic ion. If these two wells are placed in the vicinity of each other then two stationary energy states, \( \psi_s \) and \( \psi_a \) exist as shown in Figure V-D. However, the initial condition of the electron at \( t = 0 \) is that it have unit probability on the neutral atom, well 1. This can be represented in the potential well model by the linear combination of the two energy states, \( \psi_s \) and \( \psi_a \):

\[
\psi = \frac{1}{\sqrt{2}} (\psi_a + \psi_s),
\]

V-E

where \( \psi \) is the electronic state of the electron. If \( E_a \) and \( E_s \) are the energies of the wave functions \( \psi_a \) and \( \psi_s \) respectively, then Eq. V-E can be written as

\[
\psi = \frac{1}{\sqrt{2}} (\Phi_a e^{iE_a t/\hbar} + \Phi_s e^{iE_s t/\hbar}),
\]

V-F

where \( \Phi_a \) and \( \Phi_s \) are independent of time.

\( \Phi_a \) and \( \Phi_s \) can be approximated by the wave functions \( \Phi_1 \) and \( \Phi_2 \) which are the stationary electronic energy states
\[ \psi_s + \psi_a = \psi \]

**FIGURE V-D: WAVE FUNCTIONS \( \psi_s, \psi_a, \& \psi \)**
for the infinitely separated potential wells 1 and 2.

\[ \phi_a \approx (\phi_1 - \phi_2) \frac{1}{\sqrt{2}} \quad \text{V-F} \]

\[ \phi_s \approx (\phi_1 + \phi_2) \frac{1}{\sqrt{2}}. \quad \text{V-G} \]

From Eq. V-F and Eq. V-G,

\[ \psi = [\phi_1 \cos(\frac{a}{2\hbar}st) + i\phi_2 \sin(\frac{a}{2\hbar}st)]e^{i(\frac{E + E_s}{2\hbar}t)} \quad \text{V-H} \]

From Eq. V-H, when \( t = 0 \), \( \psi = \phi_1 \), and the electron is considered to be in potential well 1 as previously mentioned. However, for \( t = \hbar(E_a - E_s)/2 \), \( \psi = i\phi_2 \), and the electron has moved to potential well 2, while for \( t = \hbar(E_a - E_s) \) the electron is back to well 1. The electron will continue to oscillate between the two wells at a frequency of \( (E_a - E_s)/\hbar \).

In the case of a resonant charge transfer collision the electron from the neutral atom oscillates between the two atoms during the collision. At the end of the collision the electron may be found on either of the two atoms. The probability, \( P \), that the electron is exchanged after a collision is given by

\[ P = \sin^2 \int_0^{t_1} \frac{E_a(t) - E_s(t)}{2\hbar} \, dt, \quad \text{V-I} \]

where \( t_1 \) represents the conclusion of the collision which
began at \( t = 0 \). Eq. V-I was obtained from Eq. V-H\(^{(39)}\). Since the center of mass velocity of the colliding atoms, \( V \), is related by

\[
V = \frac{dx}{dt} \quad V-J
\]

where \( x \) is defined in Figure V-E, Eq. V-I can be rewritten as

\[
P(b,v) = \sin 2 \int_{-\infty}^{\infty} \frac{E_a(r) - E_s(r)}{2 \hbar v} dx, \quad V-K
\]

where \( b \) is the impact parameter as shown in Figure V-E, and \( r = (x^2 + b^2)^{\frac{1}{2}} \). Figure V-F shows a typical functional form for \( P(b,v) \) vs \( b \). The total cross section for charge exchange \( \sigma(v) \) can then be obtained by integrating \( P(b,v) \) over the available impact parameters,

\[
\sigma(v) = \int_{0}^{\infty} P(b,v) 2\pi b db. \quad V-L
\]

All that remains to calculate \( \sigma(v) \) is the determination of \( E_a(r) \) and \( E_s(r) \), which is one of the most difficult problems in charge exchange theory. The remaining discussion on theory will consider some of the approaches to obtaining \( E_a \) and \( E_s \), and evaluating Eq. V-L.

Rapp and Francis\(^{(40)}\), using single parameter semi-empirical hydrogen wave functions, calculated approximations
FIGURE V-F. CHARGE EXCHANGE PROBABILITY vs. b.
to \( E_a(r) \) and \( E_s(r) \), and then used them to obtain \( P(b,v) \).

From that they calculated \( b_1 = \{ b_{\text{max}}, P(b,v) = 0.25 \} \). By approximating \( P(b,v) = \frac{1}{2} \) for \( b \leq b_1 \) and \( P(b,v) = 0 \) for \( b > b_1 \), the cross section was obtained from

\[
\sigma = 2\pi \int_0^\infty P(b,v) b db \approx \frac{\pi b^2}{2}, \quad \text{V-M}
\]

as shown in Figure V-F. Solving for \( b_1 \) in terms of \( v \) the equation for the cross section becomes

\[
\sigma^{\frac{1}{2}} = -K_1 + K_2 \ln v, \quad \text{V-N}
\]

where \( K_1 \) and \( K_2 \) are only dependent on the functional form of \( E_a \) and \( E_s \).

Massey and Gilbody (41), using approximations similar to those of Rapp and Francis but with different \( E_a \) and \( E_s \) calculated a theoretical cross section as shown in Figure V-B. The potential \( E_a \) was obtained by Reagen et al (42) using 26 configurations of Slater type orbitals and \( E_s \) by Phillipson (43) using 17 configurations. These potentials were found to give theoretical results in good agreement with experimentally measured differential scattering cross sections of \( \text{He}^+ \) on \( \text{He}^0 \)(44).

The above discussion of the theoretically predicted cross sections neglects the possible complications of curve
crossing as shown in Figure V-G for He\textsuperscript{0} on He\textsuperscript{+}. The \((\sigma_g) (\sigma_u)^2\) state which goes to He(1s)\(^2\) and He(1s)\(^+\) in the case of infinite separation, crosses the \((\sigma_g)^2 (2\sigma_g)\) state of the same parity. At the crossing point the electronic state can no longer be represented as a linear combination of two states of energy \(E_a\) for \((\sigma_g) (\sigma_u)\) and \(E_s\) for \((\sigma_g) (\sigma_u)^2\), but instead three stationary electronic states are necessary to define the electronic configuration. This invalidates Eq. V-K and the cross section may not have the generally accepted functional form of Eq. V-N.

Two approximations to the curve crossing problem are often used to determine charge exchange and differential scattering cross sections. When the helium and helium ion collide in the limit of zero velocity the curve crossing is forbidden as shown in Figure V-H. In this case the charge exchange cross section is expected to oscillate as a function of collision velocity\(^{45}\). The other approximation for cases of large velocities, is that the curves cross without any mixing of the states. Effectively the curve crossing is assumed to have no effect on the electron energy states. Over the velocity range in which the cross sections were measured (1.6x10\(^6\) cm/sec to 1x10\(^7\) cm/sec) the above approximations are
**FIGURE V-G: ELECTRONIC ENERGY VS. NUCLEAR DISTANCE**

- Be$^+(1s,2p^2)$
- He$^+(1s,2s)$
- He$^+(1s)$
- He$^+(1s^2)$
- Curve Crossing

Electronic Energy

$r$, Internuclear Distance, arbitrary units
invalid \(^{46}\) and presently there is no theoretical data considering the effects of curve crossings on the charge exchange cross sections in this velocity range.

Although the presented data agree with previously measured data as shown in Fig. V-B, the presented data can not be made to fit the functional form of

\[
\sigma^H(v) = -K_1 + K_2 ln v, \quad V-H
\]

which is the predicted form of the cross section using Rapp and Francis' technique. This, however, is not an unusual occurrence. The resonant charge exchange cross sections of Li\(^+\) on Li, Na\(^+\) on Na, K\(^+\) on K and Cs\(^+\) on Cs oscillate as a function of collisional velocity. The cross section oscillations are especially dramatic in the velocity range between 5x10\(^6\) and 2x10\(^7\) cm/sec, as shown in Figure V-J\(^{47}\).

Rapid variations of nonresonant charge exchange cross sections of He\(^+\) on He\(^0\) have also been reported by de Heer\(^{48}\) within the energy range of 200 ev and 75 kev. These variations have not been theoretically predicted but are attributed to curve crossings\(^{49}\). Dworetsky et al\(^{50}\) have found oscillations in the charge exchange reaction

\[
He^+(1s) + He^0(1s) \rightarrow He^+ + He^+(1s)
\]
down to 50 eV, which Rosenthal-Foley\textsuperscript{(51)} has been able to explain on the basis of "pseudo-crossings."

In conclusion, the apparatus has been demonstrated to produce repeatable cross section measurements which are in agreement with previously published data as shown in Table V-A and Figure V-B. However, the measurements show a previously unexpected structure as a function of $E_{cm}$. As discussed, this structure could be due to a curve crossing of the electronic states of He\textsuperscript{+}. Presently measurements are being continued on this charge exchange reaction to better resolve any structure in the charge exchange cross section of He\textsuperscript{+} on He\textsuperscript{0} as a function of energy.
APPENDIX I

ENERGY ANALYZER

The design constraints on the energy analyzer are three. First, it must have sufficient resolution to reject stripped ions formed from the primary beam. If, for example, the neutral species of the primary neutral beam has an ionization energy of 10 eV then all the stripped ions formed from this beam would lose at least 10 eV in stripping. An energy analyzer would have to have an energy resolution as defined by Eq. I-A better than 1% to resolve signal ions at 1 keV from stripped ions at 0.99 keV. A resolution of 0.5% was set as a goal, which would ensure that the signal ions could be separated from the stripped ions for most neutral beams below 2 keV. Second, the energy analyzer must be less than 4 inches in length so as not to interfere with other elements in the detection chamber. Finally, the transmission of the analyzer must be as high as possible. A minimum transmission of 90% was arbitrarily set as a goal. The simplest approach to the solution would be to use a three grid
energy analyzer, as shown in Figure I-A, where grids 1 and 3 are grounded and the center grid is raised to a positive potential sufficient to allow the signal ions to pass through it but reject all ions of less energy.

The maximum energy resolution of such an energy analyzer is in part determined by the electrostatic potential drop between adjacent grid wires of the energy resolving center grid 3. If $\Phi$ is the potential of the center grid wires and $\Phi - \Delta \Phi$ is the potential between two adjacent grid wires, as shown in Figure I-B, then the maximum possible energy resolution $R$ is given by

$$R_{\text{max}}^{-1} = \frac{\Delta V}{V} > \frac{\Delta \Phi}{\Phi}$$

where $\Delta V$ is the voltage change on the center grid necessary to change the transmission of an ion beam of energy $E$ from 90% to 10%, as shown in Figure I-C, and $V$ is the maximum voltage which allows 100% transmission. The potential value $\Delta \Phi/\Phi$ can be calculated from

$$\frac{\Delta \Phi}{\Phi} = \frac{\ln \left( \frac{\pi a}{x_0} \right)}{\left[ \frac{\pi d}{x_0} - \ln \left( \frac{\pi a}{x_0} \right) \right]}$$

for the assumption $a \ll x_0$, where $x_0$ is the spacing between grid wires of the center energy resolving grid, $a$ is the
FIGURE I-A: 3 GRID ENERGY ANALYZER

FIGURE I-B: POTENTIAL VS. DISTANCE, FOR GRID WIRES
Figure 1-C: Ion Beam Intensity vs. Energy Analyzer Voltage

- V90%
- V50%
- V10% (Cutoff Voltage)

Voltage on Energy Analyzer, kV: 0.988 - 1.012
radius of the grid wires, and \( d \) is the spacing between the grids. To obtain the maximum resolution consistent with the transmission requirement given earlier, the radius of the grid wires should be made as small as possible. Assuming that the smallest practical radius for the grid wires is \( 0.00025" \) \(^{(59)}\) then the minimum spacing between wires is \( 0.0015" \), to obtain 90% transmission through three grids. Such an energy analyzer would require a grid spacing of 2.8" to obtain a resolution of 0.5%. This would make the energy analyzer at least 5.6" long.

A more practical approach is shown in Figure I-D. This energy analyzer consists of 5 grids. Grids 1 and 5 define the ground plane for the beams while grids 2 and 4 are used to slow the ions down to a few per cent of their original energy. Once the ions are slowed, grid 3 is used to resolve the energy of the ions. This technique has the advantage over a three grid system in that grids 2 and 4 electrostatically shield the resolving grid, 3, so that the potential variation between the grid wires is considerably reduced, thereby increasing the maximum possible resolution of the system. The maximum resolution of the 5 grid system is given by
\[ R_{\text{max}}^{-1} = \frac{\Delta \Phi}{\Phi} = \frac{\ln\left(\frac{na}{x_3}\right)}{\pi d_{2,3} - \ln\left(\frac{na}{x_3}\right)} \cdot \frac{V_3 - V_2}{V_3} + \frac{0.81(\ln\left(\frac{na}{x_2}\right))}{2\frac{\pi d_{1,2}}{x_2} - \ln\frac{\pi d_{1,2}}{x_2}} \cdot \frac{V_2}{V_3}, \]

which can be derived from Eq. I-B, where \( V_2 \) and \( V_3 \) are the voltages of grids 2 and 3 respectively, \( d_{2,3}, d_{1,2}, x_3 \) and \( x_2 \) are as shown in Figure I-D. For an analyzer of the dimensions shown in Figure I-D a maximum resolution of 0.25% is expected. Experimentally the resolution was measured to be 0.4% with an overall length of 1.75". The equivalent 3 grid system would be at least 6" long.

Other factors limit the resolution of the system and lead to the discrepancy between the theoretical resolution and the measured resolution of the analyzer. One such factor is caused by the lensing effect of the grid wires of grids 2, 3, and 4, which can cause ions which would normally be transmitted through the analyzer to be deflected off the axis and become lost in the analyzer. However, by attributing the difference between the calculated resolution and the measured resolution of the energy analyzer to the energy spread of the ion beams, upper limits on the energy spread of the ion beams were determined to be ~ 4 volts for ion beams originating from ion source #1 and ~ 8 volts for source
As well as being used to separate the signal ions from the lower energy ions, the five grid energy analyzer is used to determine the energy of the ions used to form ion and neutral beams. The energy of these ions is determined by the characteristic of the plasma from which they are formed as well as the voltage at which the ion source is floating. So

\[ E_{\text{ion}} = \Delta V_{\text{plasma}} + V_{\text{p.s.}} \]

where \( E_{\text{ion}} \) is the ion energy, \( \Delta V \) is the plasma potential with respect to the ion source and \( V_{\text{p.s.}} \) is the voltage at which the source is floated, which can be measured to 0.05% accuracy\(^{(60)}\). The determination of the ion energy depends only upon the measurement of \( \Delta V_{\text{plasma}} \). This can be done by experimentally determining the cutoff potential of the energy analyzer, which is defined, for convenience, to be the voltage on grid 3 such that 10% of the original intensity of the ion beam is transmitted through the energy analyzer, and comparing it to the calculated cutoff voltage. The cutoff voltage is determined by considering an ion beam of energy \( E_{\text{ion}} \) in volts and adding to it the voltage just necessary to reject all the ions of the beam. This is simply given by
\[ V_{\text{cutoff}} = E_{\text{ion}} (1 + R^{-1}_{\text{max}}). \]

Substituting Eq. I-D into Eq. I-E,
\[ V_{\text{cutoff}} = \Delta V_{\text{plasma}} (1 + R^{-1}_{\text{max}}) + V_{\text{p.s.}} (1 + R^{-1}_{\text{max}}) \]
is obtained. Solving for \( \Delta V_{\text{plasma}} \),
\[ \Delta V_{\text{plasma}} = R_{\text{max}} \frac{V_{\text{cutoff}}}{(1 + R^{-1}_{\text{max}})} - V_{\text{p.s.}}. \]

Since \( V_{\text{cutoff}}, V_{\text{p.s.}} \), and \( R_{\text{max}} \) are known, \( \Delta V_{\text{plasma}} \) can be calculated. \( \Delta V_{\text{plasma}} \) was measured to be 5.1 \( \pm \) 0.2 volts for ion source #1 used to form the neutral beam and 14.6 \( \pm \) 1 volts for ion source #2 forming the ion beam. The ability to determine the experimental cutoff voltage is demonstrated by Figure I-D, where the transmission is varied as a function of the voltage on grid 3.

Figure I-E displays the agreement between the measured cutoff voltage and the calculated cutoff voltage as a function of the voltage on grids 2 and 3.

The plasma potential can also be determined using another technique with the energy analyzer. Since the properties of the energy analyzer scale with beam energy, then
\[ \Delta V_{\text{plasma}} + V_{\text{p.s.}} = E_{\text{ion}} = KV_{50\%} \]
where \( V_{50\%} \) is the voltage on the energy analyzer which reduces the transmission of an ion beam of energy \( E_{\text{ion}} \) to 50%, and \( K \) is a constant to be determined. From Eq. I-H, if \( V_{\text{p.s.}} \) is plotted against \( V_{50\%} \) then the intercept on the x axis will equal \( \frac{\Delta V_{\text{plasma}}}{K} \). Figure I-F is such a plot, where \( K = 1.0098 \pm 7.0 \times 10^{-4} \), and \( \Delta V_{\text{plasma}} = 6 \pm 2 \) volts for ion source \#1, as determined by a least squares straight line fit to the data. Thus the plasma potential can be determined two ways, either by the comparison of the calculated and measured cutoff voltages or by extrapolating a graph of \( V_{\text{p.s.}} \) vs \( V_{50\%} \) to \( V_{\text{p.s.}} = 0 \).
Signal Ions and Background Ions

\[ d_{12} = 0.56" \]
\[ x_1 = 0.05" \]
\[ x_3 = 0.018" \]
\[ d_{23} = 0.32" \]
\[ x_2 = 0.025" \]

**FIGURE I-D: 5 GRID ENERGY ANALYZER**
FIGURE I-E: CUTOFF VOLTAGE vs $V_3 - V_2$, FOR 1 KEV BEAM

- Measured
- Calculated

Potential

$V_3 - V_2$

Volts

Cutoff Voltage, Volts -
FIGURE I-F: ION SOURCE VOLTAGE vs. 50% TRANSMISSION VOLTAGE

Slope = 1.0098 ± 0.0007

Intercept 6 ± 3 Volts
APPENDIX II

BACKGROUND GAS PRESSURE

To a large extent the background counts from the ion and neutral beams are dependent on the pressure of the detection and interaction chambers, especially at large neutral beam energies of 3 keV and above, where the energy analyzer cannot separate the stripped ions from the signal ions. Assuming a stripping cross section for a neutral beam of $1^{12} (61)$ and an interaction length of 100 cm the current of stripped ions in particles/sec is

$$I_{\text{strip}} = 300P I_N,$$  \hspace{1cm} \text{II-A}

where $P$ is the pressure in torr and $I_N$ is the neutral beam intensity in particles/sec. Then for a beam intensity of $6 \times 10^{11}$ particles/sec which is equivalent to 0.1 \(\mu\)A if each particle carries one unit of charge, e,

$$I_{\text{strip}} = 2 \times 10^{14} P.$$  \hspace{1cm} \text{II-B}

If the signal is 100 counts/sec then the background must be below $3 \times 10^5$ counts/sec to measure the signal count rate to within 10% in five hours. To obtain backgrounds on the order of $3 \times 10^5$ counts/sec or less the pressure from Eq. II-B
must be about $1 \times 10^{-9}$ torr.

Several techniques were available to obtain this pressure. The pumping speed can either be increased with cryopumps, or titanium sublimation pumps, or the outgassing of the vacuum chamber can be reduced by baking. The interaction and detection chambers were baked by infrared radiative heaters mounted in the vacuum. This technique made it possible to obtain temperatures of $150^\circ C$ to $200^\circ C$ without the necessity of using external thermal insulation. The power required to heat a given chamber depends on the losses due to convection and radiation. The power required per unit area is given by

$$P_C \approx \frac{2.21 \times 10^{-3} (\Delta T)^{5/4}}{L^{1/4}}$$

II-C(62)

and

$$P_R = \sigma \epsilon [T_C^4 - T_{lab}^4]$$

II-D

where $\sigma = 3.68 \times 10^{-11}$, the Stefan Boltzmann constant, $P_C$ is the wattage required per square inch to heat a surface $\Delta T$ above laboratory temperature due to convection loss, $L$ is the vertical height of the surface in inches, $P_R$ is the wattage loss per square inch due to radiation, $\epsilon$ is the emissivity of the heated surface, and $T_C$ is the temperature of the surface in degrees Kelvin. Using Eq. II-C and II-D a total heat load of 1.3 watts/in$^2$ was estimated to be
sufficient to obtain an average temperature of $170^\circ\text{C}$ for a chamber dimension comparable to the detection chamber of the merged beams apparatus. The actual heat input into the detection chamber to reach this temperature was measured to be 1.2 watts/in$^2$.

Another consideration of internal baking is the temperature of thermally isolated units in the chamber. Since these units can lose heat only by re-radiation and not by conduction, their temperature is considerably higher. The temperature of these thermally isolated elements can be calculated by equating the power density absorbed by the chamber wall to the Stefan Boltzmann equation. Since the chamber wall radiates power back into the vacuum chamber and out into the lab, the power density absorption is $P_c + 2P_R$ and the temperature of an isolated unit is

$$T_{\text{isolation}} = \frac{(P_c + 2P_R)^{1/4}}{\epsilon} \cdot \sigma^{-1/4}, \quad \text{II-E}$$

where $P_c$, $P_R$, $\epsilon$, and $\sigma$ are as previously defined and $T_{\text{isolation}}$ is in degrees Kelvin. In typical bakeouts $T_{\text{isolation}}$ ranges from $280^\circ\text{C}$ to $300^\circ\text{C}$, which is within the acceptable thermal levels for teflon insulation$^{(63)}$ and for the ceramic bolometer used to calibrate fast neutral beams$^{(64)}$.

By baking the detection chamber to an average tempera-
ture of 170°C an ion guage pressure of 3.6x10^{-10} torr was obtained. This was found to be in general agreement with published outgassing data. Stainless steel baked to 150°C outgasses H_2 at 2x10^{-12} torr-1/sec-cm^2 (65) and viton outgasses H_2O at 5x10^{-9} torr-1/sec-cm^2 (66). For the detection chamber of 1.5x10^4 cm^2 area of stainless steel, 200 cm^2 of viton, and a pumping speed of 3000 l/sec for H_2O an ultimate calculated pressure of 3x10^{-10} torr is obtained. Double viton O-rings (67), as in Figure II-A, were used to ensure that the O-rings would degass sufficiently during baking to obtain the published outgassing rate. After each bake, it was found that the double O-ring groove could be vented to air with no degradation in vacuum.

With an operating pressure of 5x10^{-10} to 2x10^{-9} torr it was possible to operate the apparatus up to 3 keV neutral beam energy, without large dead time corrections and extended counting times over 60 minutes. At higher energies however the stripping became so large that accurate cross section measurements were impossible.
Figure II-A

DOUBLE O-RING DETAIL
APPENDIX III

TRANSIT TIME EFFECTS

This section is concerned with the effects of the transit time of the ion and neutral beams through the apparatus. Consider Figure III-A, which schematically represents the beams, the signal and the counting periods in time. Considering the counting periods 1 through 4, the counts registered in scalers 1 and 2 are

Scaler #1 Counts = \( \text{BG}_N(T_{P_1} - t + t') + \text{St}_N + T_{P_3} \text{BG}_I; \) III-A

Scaler #2 Counts = \( \text{BG}_I(T_{P_2} - t + t') + S(T_{P_2} - t_i) + T_{P_2} \text{BG}_N; \) III-B

where the variables \( t_i \), \( t' \), \( t_N \), \( t' \) are as shown in Figure III-A, and \( S \) is the signal count rate in counts/sec. When the positions of the ion and neutral beams are interchanged, then

Scaler #1 Counts = \( \text{BG}_I(T_{P_1} - t + t') + \text{St}_I + T_{P_3} \text{BG}_N; \) III-C

Scaler #2 Counts = \( \text{BG}_N(T_{P_2} - t + t') + S(T_{P_2} - t_i) + T_{P_2} \text{BG}_I. \) III-D

By summing Eq. III-A and Eq. III-C, and Eq. III-B and Eq. III-D:
Total Counts of Scaler #1 = \( BG_1(T_{p_3} + T_{p_1} - t^I_I + t^I_I) \)

\[ + BG_N(T_{p_3} + T_{p_1} - t^N_N + t^N_N) \]

\[ + S(t^N_N + t^I_I), \quad \text{III-E} \]

and

Total Counts of Scaler #2 = \( BG_N(2T_{p_2} - t^N_N + t^N_N) \)

\[ + BG_1(2T_{p_2} - t^I_I + t^I_I) \]

\[ + S(2T_{p_2} - t^I_I - t^N_N). \quad \text{III-F} \]

Taking the numerical difference of scalars 2 and 1, \( S_m^I \) is obtained:

\[ S_m^I = S[2T_{p_2} - (t^I_I + t^N_N + t^I_I + t^N_N)] \]

\[ + BG_N(T_{p_3} + T_{p_1} - 2T_{p_2}) \]

\[ + BG_1(T_{p_3} + T_{p_1} - 2T_{p_2}). \quad \text{III-G} \]

The sum of the times \( T_{p_3} \) and \( T_{p_1} \) ha been measured to be equal to \( 2T_{p_2} \) and therefore

\[ T_{p_3} + T_{p_1} - 2T_{p_2} = 0. \quad \text{III-H} \]

Further measurements show that \( t^N_N \not\equiv t^N_N \) and \( t^I_I \not\equiv t^I_I \). Eq. III-D can thus be rewritten

\[ S_m^I = 2S(T_{p} - t^I_I - t^N_N), \quad \text{III-I} \]
since the signal count, $S_m^*$, represents the number of counts arriving in two counting periods of $T_p$. Then the counts/sec $S_m$ is

$$S_m = \frac{S_m^*}{2T_p} = S_p \frac{T_p - t_I - t_N}{T_p} \quad \text{III-J}$$

Solving for $S$:

$$S = \frac{S_m T_p}{T_p - t_I - t_N} \quad \text{III-K}$$
APPENDIX IV

DEAD TIME CORRECTION

The dead time of the counting electronics causes production of a spurious signal. To relate this signal to other known parameters consider

\[ R = \frac{R_m}{1 - T_D R_m}, \quad \text{IV-A} \]

where \( R \) is the count rate arriving at the input of an electronic counting system with an inherent dead time \( T_D \), and \( R_m \) is the measured count rate. Solving the above equation for \( R_m \) and assuming \( 1 \gg T_D R_m \),

\[ R_m = R(1 - T_D R) \quad \text{IV-B} \]

is obtained. Using Eq. IV-B the actual count rates can be related to the measured count rates for the four counting periods of the beam chopping sequence by

\[ R_{m_1}^i = B G_i (1 - T_{D} B G_i), \quad \text{IV-C} \]

\[ R_{m_2}^i = [B G_i + B G_n + S][1 - T_{D}(B G_i + B G_n + S)], \quad \text{IV-D} \]

\[ R_{m_3}^n = B G_n (1 - T_{D} B G_n), \quad \text{IV-E} \]
\[ R_{m_4} = 0, \quad \text{IV-F} \]

where \( R_{m_1} \) is the measured count rate with the ion beam on, 
\( R_{m_2} \) is measured with both beams operating, \( R_{m_3} \) with the neutral beam, and \( R_{m_4} \) with all the beams off. BG \(_i\) and BG \(_n\) are the background count rates from the ion and neutral beams respectively, and \( S \) is the signal count rate.

Taking the difference of \((R_{m_1} + R_{m_4})\) and \((R_{m_2} + R_{m_3})\) the measured ion signal \( S_m \) is obtained:

\[ S_m = S - 2T_D[BG_iBG_n + S(BG_i + BG_n + \frac{S}{2})]. \quad \text{IV-G} \]

Solving for \( S \) assuming that \( BG_iBG_n \gg S(BG_i + BG_n + S/2) \)

\[ S = S_m + 2T_DBG_iBG_n. \quad \text{IV-H} \]

If a counting sequence is run with only one beam on then the count rate in either scaler is

\[ BG_i = \frac{1}{2}BG_i, \quad BG_n = \frac{1}{2}BG_n. \quad \text{IV-I, J} \]

\( S \), which is the signal received during only one period of a four period counting sequence, can be related to \( S_{\text{actual}} \) by

\[ S_{\text{actual}} = 4S, \quad \text{IV-K} \]

where \( S_{\text{actual}} \) is the received signal assuming that signal counts were produced during all four counting periods. From Eq. IV-H, IV-I, IV-J, IV-K, we can obtain

\[ S_{\text{actual}} = 4(S + 8BG_iBG_nT_D). \quad \text{IV-L} \]
APPENDIX V

FRINGING FIELD OF THE Merging MAGNET

The majority of the fringe magnetic field from the merging magnet arises from the edges of the polar faces. Assuming that for large distances from the magnet's poles the fringing field can be approximated by two lines of magnetic charge, as below,

![Diagram of magnetic charge lines](image)

where $D$ is the length of the poles and $d$ is the distance between the center of the poles, then the field $B(x)$ a distance $x$ from the midpoint between the pole edges is given by

$$B = 4 \int_{0}^{D/2} \frac{dk}{(x^2 + \frac{d^2}{4} + y^2)^{3/2}} \ dy = \frac{Ddk}{(x^2 + \frac{d^2}{4})(x^2 + \frac{d^2}{4} + \frac{D^2}{4})^{1/2}}, \quad V-A,B$$

where $K$ is a constant to be determined. For the merging magnet $D = 4''$ and $d = 2''$; then Eq. V-A becomes
\[ B = \frac{8K}{(x^2 + 1)(x^2 + 5)^{\frac{3}{2}}} \quad V-C \]

By fitting Eq. V-C to the fringing field it was found that \( K = 0.17B_0 \) where \( B_0 \) is the maximum field between the poles of the magnet.
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