A Study of He+ + Ar Collisions at Energies Between 600 eV & 1500 eV

Alton Dull Jr.
Western Kentucky University

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Dull,

Alton H., Jr.

1977
A STUDY OF He$^+$ + Ar COLLISIONS AT ENERGIES BETWEEN
600 eV AND 1500 eV

A Thesis
Presented to
the Faculty of the Department of Physics and Astronomy
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Alton H. Dull, Jr.
May 1977
A STUDY OF He$^+$ + Ar COLLISIONS AT ENERGIES BETWEEN 600 eV AND 1500 eV

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Director of Thesis

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(Date)

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This investigation was undertaken in order to confirm and to extend earlier studies of processes whereby energy and angular momentum are transferred from external to internal degrees of freedom in low velocity collisions between ions and atoms. Specifically, this investigation sought to verify the proper functioning of a device designed to study low velocity atomic and molecular collisions, to confirm results obtained in an earlier study of spectra produced by collisions of He$^+$ ions with argon atoms, and to extend the energy and wavelength ranges of this study to 1500 eV and 6200 Å, respectively.

The data was in the form of stripchart recordings taken at five beam energies, 600 eV, 800 eV, 1000 eV, 1250 eV, and 1500 eV. A basic analysis of this data was carried out; i.e., lines were identified, their wavelengths determined, and intensities calculated. In addition, the energy dependencies of the emission cross sections of twelve fully resolved lines were plotted and a partial Grotian diagram was drawn.

The apparatus was found to be functioning properly at energies about 600 eV but not at lower energies. Lipeles' energy and wavelength ranges were extended successfully, and in several instances his findings were confirmed (cf. Lipeles
1971). The visible Ar II spectrum was quite rich with twenty-nine lines being observed, six of which had not been detected previously. In addition, a single line was observed from neutral argon and a single band from molecular nitrogen, a contaminant in the argon target gas.
INTRODUCTION

According to early collision theory, Born's approximation\(^1\) and the adiabatic criterion,\(^2\) collisions involving atoms and molecules with relative velocities less than \(10^7\) cm/sec are incapable of producing a significant amount of radiation. It was thought that the process by which the kinetic energy of the colliding bodies is transferred to internal electronic energy was very inefficient at low energies.

However, in the 1920's significant evidence in the form of meteor spectra was obtained which contradicted this theory. Examination of the available spectra revealed that meteors produce far more radiation and that their luminosity is much less dependent on velocity than would be expected if all slow collisions were near-adiabatic.

In 1932, Landau and Zener developed a quantum mechanical model for low energy collisions which seemed to explain the meteoric phenomena. In this model the potential energy curves of the colliding bodies are greatly modified as the internuclear separation decreases until they nearly cross at approximately 1 atomic unit forming a pseudo-crossing.\(^3\) Collisions with small enough impact parameters are capable of passing through the pseudo-crossing at which point the probability for energy transfer is greatly increased.
However, it was not until 1965 when Lipeles, Novick, and Tolk—at Columbia University—observed cross sections of the order of $10^{-16} \text{ cm}^2$ for $\text{He}^+$ ions impacting on $\text{Xe}$ at 10 eV that conclusive evidence was obtained which proved that not all low velocity collisions are near-adiabatic.\(^4\)

In the years following, improved experimental techniques were developed and much information concerning ion-neutral and ion-molecular collisions was gathered. It was discovered that, in addition to the large values for some cross sections at energies slightly above the final state energy, certain cross sections exhibit an oscillatory structure strongly dependent on projectile energy.

Dworetsky, Novick, Smith, and Tolk in 1967 explained these phenomena in terms of the molecular-potential curve crossing model proposed by Landau and Zener.\(^5\) The large values of the cross section near threshold were interpreted as arising from pseudo-crossing of the ground state and excited state molecular-potential energy curves occurring at an internuclear separation $R_1$ of about one atomic unit as shown in Figure 1(a). The oscillatory structure was attributed to phase interference effects which develop during the double passage of the system through the crossing at $R_1$.

Two years later, Rosenthal and Foley showed that the phase interference effects lead to oscillations in the differential inelastic cross section but do not explain the oscillations in the total cross section.\(^6\) They concluded that in addition to the pseudo-crossings at $R_1$, other
Figure 1. Diagramatic comparison of the single-crossing region and the two-crossing region models: (a) Two-level crossing scheme. (b) Three-level, two-crossing scheme.
pseudo-crossing between two or more excited states existed at larger values of internuclear separation, $R_2 \approx 15-40$ atomic units as shown in Figure 1(b). They considered the oscillatory structure to arise when two excited states populated at $R_1$ developed a phase difference between $R_1$ and $R_2$. Since this phase difference was only weakly dependent on the impact parameter, it manifested itself in the form of oscillations in the total cross sections.

Following the work by Novick, et. al. and by Rosenthal and Foley, a number of experimental and theoretical studies of excitation in slow collisions between heavy particles have been reported. Of particular interest in connection with the origin of meteor spectra is a paper by Boitnott and Savage. These authors used a crossed beam technique to measure emission cross sections for the sodium D lines produced by collisions of sodium atoms with Ar, Ar$^+$, He, He$^+$, O$_2$, O$_2^+$, N$_2$, N$_2^+$, and N$^+$ for energies from 150 eV to 2000 eV. They found that the emission cross sections are large (of the order of $10^{-15}$ cm$^2$), as expected from studies of meteor spectra, and that collisions involving gas ions are approximately three times more efficient in generating the D lines than collisions involving neutral particles alone.

In relation to the present work, a paper published in 1970 by M. Lipeles is of special importance. Lipeles investigated spectra produced by collisions of argon atoms with He$^+$ ions having energies of 10 eV to 1000 eV. He found that the most numerous and intense lines in the wavelength range studied, 3500 Å to 5200 Å, resulted from charge
exchange between the He$^+$ ion and argon atom with simultaneous excitation of the Ar$^+$ ion thus formed. The strongest of these lines were produced by transitions of the 4p electron from two configurations of Ar$^+$, namely, 3s$^2$3p$^4$(1D)4p and 3s$^2$3p$^4$(3P)4p. The intensities of lines arising from transitions out of the former configuration tended to fall off rapidly with decreasing orbital angular momentum of the upper term.

The present investigations were undertaken in order to extend the previous studies of the processes whereby energy and angular momentum are transferred from external to internal degrees of freedom during slow collisions between ions and atoms. Specifically, the purposes of this work were to check the findings of Lipeles and to extend the energy and wavelength ranges of his results to 1500 eV and 6200 Å, respectively. It should be noted that the validity of Lipeles' findings was not and is not in question. On the contrary, his results had to be reproduced in order to insure that the apparatus used in these experiments, which had been disassembled and shipped from Cambridge, Massachusetts, was operating properly after reassembly at Western Kentucky University. Otherwise, the reliability of new results obtained in this work might have been questionable.
II. EXPERIMENTAL APPARATUS

The apparatus consists of a vacuum system and components which form an ion beam, allow it to collide with a target gas, and detect light produced in the collisions. Many of the components are housed in three nearly separate regions of the vacuum system as indicated by the dashed enclosures in Figure 2. The source region and optical region are connected by two inch copper tubing and are evacuated by a single four inch oil diffusion pump attached to the source region. The interaction region is evacuated by a six inch diffusion pump. Both pumps are equipped with zeolite traps to minimize back-streaming of oil to the vacuum system. During these experiments the ultimate pressure in all sections of the apparatus was $6 \times 10^{-6}$ Torr.

**Source Region**

Ions are produced in the source region by electron bombardment of the desired beam material in a magnetically confined discharge. In these experiments Airco grade 4.5 helium gas, allegedly 99.995% pure, was employed as the beam material. The gas was filtered through a zeolite trap at dry ice temperature to remove condensable impurities before being leaked into the discharge chamber.
FIGURE 2. SCHEMATIC DIAGRAM OF THE ATOMIC BEAM APPARATUS

- **SOURCE REGION**
  - extraction/lens system
  - analyzer magnet and drift tube
  - final lens

- **INTERACTION REGION**
  - discharge chamber
  - charge exchange chamber
  - ion deflecting plates
  - collision chamber
  - collision volume
  - faraday cup

- **OPTICAL REGION**
  - ellipsoidal mirror
  - standard lamp & optics
  - quartz windows
  - monochromator
  - electrometer
  - electrometer and stripchart recorder
  - photomultiplier (-78°C)
Ions are withdrawn from the discharge by a conical extraction electrode and are formed into a ribbon shaped beam, approximately 2 mm wide and 10 mm high, by an einzel lens followed by two electrostatic quadrupoles. The beam then enters the drift tube of a three inch radius, 90° sector, magnetic mass analyzer where virtually all remaining impurities are removed. Upon passing through the exit slit of the drift tube, the beam encounters a final electrostatic lens which controls the trajectories of the ions as they accelerate or decelerate to the proper collision energy before entering the interaction region.

The collision energy is determined by the potential difference between ground and a variable positive voltage applied to the discharge chamber. This voltage also serves as a reference for a power supply which maintains a constant potential difference across a divider network that supplies voltages to the extractor, lenses, and drift tube. This design allows the beam to be formed and mass analyzed at a fixed high energy, 1000 eV in these experiments, thereby avoiding losses of current which otherwise would result from space charge dispersion of the beam at low collision energies.

Typically, thirty microamps of current strike the entrance slit of the drift tube, and one or two microamps leave the exit slit. Some of this current is lost each time the beam passes through an aperture on its way to the collision volume, with the result that currents traversing the collision volume in these experiments ranged from...
3.0 x 10^{-8} \text{ amps at 600 eV to } 2.5 \times 10^{-7} \text{ amps at 1500 eV. These currents were stable to ±3% or better during any particular scan of a spectral region.}

**Interaction Region**

After leaving the final lens, ions pass into the interaction region and through the charge exchange chamber, where they may be neutralized by transfer of electrons from a suitable gas. The charge exchange chamber is primarily employed in the studies of neutral-neutral collisions and is kept evacuated for studies of ion collisions. In either type of work, however, its entrance slit serves as the first of two collimating apertures which define the beam in the collision chamber. The entrance slit of the collision chamber itself serves as the second collimating aperture. Together these two slits insure that all ions entering the collision chamber are collected by the faraday cup unless they are deflected from their original paths by encounters with target gas molecules. The collimating apertures, with their dimensions and an outline of the beam, are shown schematically in Figure 3.

The collision volume, where ions and target gas molecules interact, is located just inside the collision chamber. Its breadth and height are determined by the intersection of the beam with the target gas, while its length is fixed by the distance (25.0 mm) between the entrance slit of the collision chamber and the slightly oversized entrance slit of the faraday cup. The current
FIGURE 3. SCHEMATIC OF SLIT GEOMETRY

FINAL LENS

CHARGE EXCHANGE CHAMBER

COLLISION VOLUME

$W_0 = 1.0 \text{ mm}$
$H_0 = 10.0 \text{ mm}$
$L_0 = 83.0 \text{ mm}$

$W_1 = 2.12 \text{ mm}$
$H_1 = 10.00 \text{ mm}$
$L_1 = 108.0 \text{ mm}$

$W_2 = 0.40 \text{ mm}$
$H_2 = 6.25 \text{ mm}$
$L_2 = 25.0 \text{ mm}$

$W_3 = 1.0 \text{ mm}$
$H_3 = 10.0 \text{ mm}$

$W = \text{SLIT WIDTH}$
$H = \text{SLIT HEIGHT}$
$L = \text{DISTANCE BETWEEN SLITS}$
passing through the collision volume is measured by a calibrated electrometer attached to the Faraday cup. The collision chamber also contains a thermistor for measuring the target gas temperature, a port leading to a capacitance manometer for measuring target gas pressure, and electrodes for suppressing secondary electrons and collecting slow ions produced by collisions.

The target gas used in these experiments was Airco grade 5.5 argon; it was allegedly 99.999% pure but was found by mass analysis to contain about 10% $N_2$, 2% $O_2$, and a detectable amount of water vapor. Target gas temperature ranged from 22.5°C to 24.3°C but was quite stable during any particular scan of a spectral region. Target gas pressure was kept below $10^{-3}$ Torr to avoid multiple collisions and fluctuated by as much as ±5% during a scan. The capacitance manometer was not calibrated in this work, but the experience of others with these devices indicated that the force calibrations supplied by the manufacturers are at least as reliable as calibrations against McLeod gauges. 10

**Optical Region**

Light from the collision volume is reflected onto the entrance slit of a 0.3 meter, f/5.3 McPhearson grating monochromator by an ellipsoidal mirror whose foci lie at the center of the collision volume and the center of the monochromator's entrance slit. This mirror, after being rotated 180°, is also used to reflect light from a standard lamp onto the monochromator's entrance slit. The aperture
of the mirror exceeds that of the monochromator so that the amount of light collected by the optical system is determined by the monochromator's aperture. A grating ruled with 1200 lines/mm and blazed for 5000 Å in the first order was used in these experiments; it gave a first order dispersion of 26.5 Å/mm at the exit slit.

Light passing through the exit slit of the monochromator is detected by an Amperex 56 TUVP photomultiplier with a quartz window and an S-20 photocathode. The photomultiplier is cooled to -78°C by a dry ice and alcohol bath in order to reduce its dark current to $2 \times 10^{-10}$ amperes. In these experiments a calibrated electrometer and stripchart recorder were used to register the photomultiplier current.
III. EXPERIMENTAL PROCEDURE

Data were taken at five beam energies: 600 eV, 800 eV, 1000 eV, 1250 eV, and 1500 eV. At each energy an initial scan from 3100 Å to 6200 Å was taken with 500 micron slits to determine which wavelength intervals contained detectable amounts of radiation. Each interval was then scanned with narrower slits until the maximum resolution of its weakest spectral feature was obtained. The wavelength range, slit width, and scan rate for each interval are listed in Table 1. All intervals were scanned at least twice and additional scans, up to five in number, were taken when agreement between successive traces appeared to be poor.

In order to provide a wavelength reference $X(\lambda)$ within each interval, the monochromator setting was recorded at the start of the trace. Other essential variables such as beam current, target gas temperature, and target gas pressure were also monitored during each scan. The target gas temperature, which was quite stable, was recorded only at the beginning of each trace; however, the beam current and target gas pressure, which sometimes drifted during a scan, were recorded at both the beginning and the end of a trace.

In order to estimate the relative intensities and emission cross sections of the spectral features, it was necessary to know the fraction of the collision light
TABLE 1.

A list of the scan segments with the slit widths and scan rates used to scan each segment.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Slit Width</th>
<th>Scan Rate</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Microns</td>
<td>A/min</td>
</tr>
<tr>
<td>3510 - 3625</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>3900 - 4200</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>4185 - 4520</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>4520 - 4600</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>4600 - 4630</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>4640 - 4755</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>4755 - 4825</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>4860 - 4910</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>4910 - 5210</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>5830 - 5975</td>
<td>500</td>
<td>50</td>
</tr>
<tr>
<td>6075 - 6200</td>
<td>500</td>
<td>50</td>
</tr>
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admitted to the monochromator by slits of different widths and also to know the response of the optical system to light of different wavelengths. The fraction of collision light passed by slits of different widths was determined by setting the monochromator at zero order and recording the photomultiplier current while varying the slit width. As can be seen from the graph in Figure 4, one hundred percent of the collision light reflected by the ellipsoidal mirror passes into the monochromator with 2000 micron slits.

The response of the optical system as a function of wavelength was determined as follows. Light from a G.E. 1053 standard lamp, placed above the collision region, was passed through neutral density filters to reduce its intensity and through a narrow band interference filter to suppress scattered light in the monochromator. After entering the vacuum housing through a quartz window, the calibration light was reflected onto the entrance slit of the monochromator by the ellipsoidal mirror which had been rotated 180° from its normal position (facing the collision volume). See Figure 2. With the monochromator slits set at 500 microns, scans were taken across the 50 Å band pass of each of nine interference filters whose central transmitted wavelengths were equally spaced every 400 Å from 3100 Å to 6300 Å. The wavelength setting of the monochromator was recorded at the start of each scan and the wavelengths of the peaks were determined from these reference points by a procedure described in the next section. Peak photomultiplier currents \( J(\lambda) \) were read from the stripcharts. The response of the optical system in
FIGURE 4. THE FRACTION OF COLLISON LIGHT PASSED BY THE ENTRANCE SLIT OF THE MONOCHROMATOR.
arbitrary units was then calculated from the equation,

\[ K(\lambda)C = \frac{J(\lambda)}{t_{nd}t_{if}R(\lambda)} \]

whose derivation is described in Appendix I. In this equation \( t_{nd} \) is the combined transmittance of the neutral density filters, \( t_{if} \) is the peak transmittance of the interference filter, and \( R(\lambda) \) is the central radiance of the standard lamp at the peak wavelength \( \lambda \). Values of \( t_{nd} \) and \( t_{if} \) were obtained from transmittance curves supplied by the manufacturer of the filters, and values of \( R(\lambda) \) were read from the calibration curve of the standard lamp. The response curve of the optical system thus determined is shown in Figure 5. Since the ordinate contains the unknown factor \( C \), spectral responses read from this graph cannot be used to obtain absolute light fluxes from the photomultiplier currents. However, only relative intensities and emission cross sections in a single set of arbitrary units are required in this work. Both can be calculated using values of \( K(\lambda)C \) read from the response curve because the factor \( C \) is nearly constant as demonstrated in Appendix II.
FIGURE 5. THE SPECTRAL RESPONSE OF THE OPTICAL SYSTEM

![Graph showing the spectral response of the optical system with wavelength (Å) on the x-axis and $K(\lambda)C (10^{-14}$ ergs cm$^{-2}$ steradians Å$^{-1}$ sec photons$^{-1}$) on the y-axis.]
IV. DATA ANALYSIS

Wavelengths

The initial step in the data analysis was to determine the wavelengths of the spectral features. These were obtained from stripchart recordings by multiplying the distance D, measured from a reference point X(λ) of known wavelength to the center of the feature, by the ratio of the monochromator scan rate (Å/min) to the chart speed (in/min). Several wavelengths were obtained for each feature from the recordings at the five beam energies and were then averaged. A factor of 4.5 Å was then subtracted from each average to correct for a zero order shift produced by the positioning of the monochromator's grating in its holder. The wavelengths thus calculated were then rounded to the nearest angstrom (Å). These wavelengths can be assumed accurate to within 2.0 Å for fully resolved features and 5.0 Å for blends. This is reasonable since the centers of the features were estimated and the mechanical drives of the monochromator and stripchart recorder exhibited a combined play of 1.0 Å.

Blending Classifications

Each feature was classified as resolved (R), partially blended (PB), or blended (B) based on its symmetry, its base width, and the proximity of other features. However, some
features were classified and treated as resolved although they were known to be partially blended. This procedure was followed whenever the contributions of blending to the overall intensity appeared to be less than or equal to the estimated experimental error in the line's intensity. In these experiments the accuracy with which a line's intensity could be determined was dependent almost entirely on the noise level which was approximately 5% of the normalized 4610 Å line intensity.

Transitions and Upper Terms

The transitions which produced the spectra were identified by considering all known Ar I, Ar II, He I, and He II lines within 0.8 base width of each feature's central wavelength as possible contributors to that feature. Bands of $O_2$, $O_2^+$, $N_2$, $N_2^+$, and $H_2O$ were also considered as possible contributors because the target gas contained small amounts of these substances. Consideration was limited to those lines and bands within 0.8 base width of the peaks because any line or band capable of contributing a significant amount of radiation to a feature (20% or more of the maximum intensity) appears as a distinct shoulder on that feature if it is more than 0.8 base width from the peak. Known lines and the transitions responsible for them were obtained from "Tables of Spectral Lines of Neutral and Ionized Atoms" by Striganov and Sventitskii and from "A Multiplet Table of Astrophysical Interest" by C. E. Moore. The same type of information for bands was obtained from "The Identification Of
Molecular Spectra by Pearse and Gaydon. A list of all upper terms was then compiled and a count was taken of the number of times each upper term occurred in the list. Those terms occurring less than five times were assumed not to have been populated by the collisions unless a resolved line or band was observed which in fact arose from such a term. Of course, the occurrence of a term five or more times in a list compiled as described does not prove that the term was populated by the collisions or vice versa. Nevertheless, this criterion, while arbitrary, is perhaps as satisfactory as any, given the limited resolution of the spectra.

Relative Intensities

The relative intensities of the spectral features were obtained as follows. The flux collected by the monochromator was calculated in an arbitrary set of units from the peak photomultiplier current \( J(\lambda) \) using the relation,

\[
\phi(\lambda) = \frac{J(\lambda)}{K(\lambda)C}
\]

This flux was then corrected to a full slit width, unit beam current, and unit target gas density to obtain normalized intensities.

\[
\text{Normalized Intensity} = \frac{\phi(\lambda)}{F \cdot T \cdot N}
\]

Values of \( F \) and \( K(\lambda)C \) used in these equations were read from the graphs in Figures 4 and 5. The mean beam current \( \overline{I} \) and target gas pressure \( \overline{P} \) were determined by averaging their
respective values at the beginning and end of each scan. Then, since target gas temperature was constant during a scan, the mean target gas density \( \bar{N} \) was calculated from \( \bar{P} \) by means of the ideal gas equation,

\[
\bar{N} = \frac{\bar{P}}{kT}
\]

where \( k \) is Boltzman's constant \( (k = 1.38 \times 10^{-23} \text{ Joules/}^\circ\text{K}) \). At least two and often several values were obtained for a feature's normalized intensity at each energy. These values, calculated from repeated scans, were averaged to obtain the feature's mean normalized intensity at the beam energy in question.

Once the normalized intensities had been calculated, the relative intensities were obtained by dividing all normalized intensities by the 4610 \( \bar{\text{A}} \) line's normalized intensity at the beam energy in question.

\[
\text{Relative Intensity} = \frac{\text{Feature's Normalized Intensity}}{4610 \bar{\text{A}} \text{ Line's Normalized Intensity}}
\]

Relative intensities calculated in this way give only a crude indication of the comparative strengths of the spectral features for two reasons. First, a blended feature's peak intensity is only a rough measure of its total intensity because lines of several wavelengths contribute to the feature's peak intensity and shape. (This is not a problem in the case of resolved lines because these features have nearly the same shapes and base widths, and therefore their total intensities are directly proportional to their respective peak intensities.)
Second, the relative intensities calculated here are relative intensities of the radiation collected by the monochromator, not necessarily the relative intensities of the radiation emitted from the collision volume. The distinction arises because the spatial distribution of the light may not be the same at different wavelengths owing to differences in the polarization of the lines. This effect is discussed further in Appendix II. Nevertheless, despite these limitations, the relative intensities are useful for conveying a general picture of the comparative strengths of the spectral features and the variations of the comparative strengths with beam energy.

**Emission Cross Sections**

Emission cross sections of resolved lines were calculated from the equation,

\[(\text{Constant})\sigma(\lambda) = \frac{J(\lambda)}{F \cdot K(\lambda) \cdot C \cdot I \cdot N}\]

Values of the quantities on the right hand side of this equation were obtained as they were for the calculations of relative intensities. Since polarization of the light has been neglected, the emission cross sections may be in error by as much as 50% from this cause alone. The derivation of the last equation and the errors in cross sections and relative intensities of resolved lines caused by neglect of polarization are described in Appendix II.
V. RESULTS AND DISCUSSION

Spectral Features

The visible Ar II spectrum was quite rich as is evidenced by the graphical representations of the spectra taken at the five beam energies, Figures 6-10. The graphs consist of vertical lines each of which represent an observed spectral feature. Each line is positioned according to the feature's central wavelength and is labeled as to the atomic species and upper term of the feature's primary component. A line's height represents the feature's intensity relative to the intensity of the 4610 Å feature which has been normalized to 100 units. Although the 4610 Å feature's intensity is the same in each graph, the intensities of the other features vary with energy. This intensity variation suggests that the amount by which the collisions populate a particular upper term is dependent on the collision energy. Several features were not detected at energies less than 1000 eV. Consequently, they do not appear in the graphs of the lower energy spectra. This does not necessarily mean that the upper terms of these features were not populated by the lower energy collisions, but rather that the populations were too small to produce a signal strong enough to be discerned from the noise.
FIGURE 6. THE 600 eV SPECTRUM
Figure 7. The 800 eV Spectrum

Relative Intensity vs. Wavelength (Å)
FIGURE 8. THE 1000 eV SPECTRUM
FIGURE 9. THE 1250 eV SPECTRUM
FIGURE 10. THE 1500 eV SPECTRUM
In all, thirty-one features were observed and positively identified, twenty-nine of which were Ar II lines. The remaining features, which will be discussed later, were produced by neutral argon (Ar I) and nitrogen (N₂), respectively.

All Ar II lines whose upper terms could definitely be identified arose from the following terms: 4p'²F⁰, 4p'²P⁰, 4p'²P⁰, 4d²D⁰, 4p²P⁰, 4p²S⁰, 5s²D⁰, 4p⁴D⁰, and 4d²G. Several additional terms were assumed to be populated based upon a frequency count of the possible occurrences of lines from these terms within 0.8 base width of the peaks of the observed features. These terms are presented in Table 2 along with the Ar I terms which were also assumed to be populated. Lipeles detected weak emissions from several of the Ar II terms, also indicated in the table. Lipeles also reported observing several weak Ar I emissions, but the terms responsible for these emissions were not specified.

Observed transitions from the nine Ar II upper terms, which were definitely known to be populated by the collisions, are summarized in Figure 11. In the figure a line connecting an upper term with a lower term represents one or more of the spectral lines in the multiplet produced by the transitions between these terms. All observed Ar II lines resulted from transitions between terms whose energy levels lay between 24.68 eV and 16.85 eV above ground state. The most frequently occurring transitions were those emanating from the heavily populated 4p' terms; these involved energy levels between
TABLE 2

A list of the Ar I and Ar II terms which were assumed to be populated based solely on the number of possible occurrences of lines from these terms in the observed spectrum. An asterisk (*) denotes those terms from which Lipeles observed weak emissions.

<table>
<thead>
<tr>
<th>Ar I</th>
<th>Ar II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5p(1\frac{1}{2})$</td>
<td>$4p^4p^0$</td>
</tr>
<tr>
<td>$6d(\frac{1}{2})^0$</td>
<td>$4p^4s^0$</td>
</tr>
<tr>
<td>$7s(1\frac{1}{2})^0$</td>
<td>$5s^2p$</td>
</tr>
<tr>
<td>$11s(1\frac{1}{2})^0$</td>
<td>$4d^4p$</td>
</tr>
<tr>
<td></td>
<td>$4d^4d$</td>
</tr>
<tr>
<td></td>
<td>$5s^4p$</td>
</tr>
<tr>
<td></td>
<td>$^3P_0 4f[3]^0$</td>
</tr>
<tr>
<td></td>
<td>$^3P_1 4f[2]^0$</td>
</tr>
</tbody>
</table>
FIGURE 11. A PARTIAL CIROTIAN DIAGRAM OF THE Ar II SPECTRUM
21.41 eV and 18.37 eV above the ground state. In addition, two terms participated in a cascade process. The 5s'2D term contributed to the populations of each of the 4p' terms. The 4d'2G term contributed only to the population of the 4p'2F0 term. Although a quantitative analysis of the effects of cascade on the intensities of the 4p' lines was not carried out, there is little doubt judging from the strengths of the 5s'2D and 4d'2G lines that the contributions were sizeable.

Although several features could not be completely resolved in these experiments, their measured wavelengths agree with standard wavelengths to within 2.0 Å, as expected. Unfortunately, the differences in the intensities of the spectral features did not allow the spectrum to be scanned with a constant slit width. The weaker portions of the spectrum had to be scanned with wider slits to obtain a more favorable signal to noise ratio. Consequently, only the segment closely surrounding the 4610 Å line could be scanned with 100 μ slits. The remainder of the spectrum was scanned with either 200 μ or 500 μ slits as indicated in Table 1. This resulted in a resolution which was at best 2.6 Å, but was often much poorer, ranging between 5.2 Å and 13.2 Å. Lipeles on the other hand was able to scan the entire spectrum with 100 μ slits providing him with a constant 2.6 Å resolution. Although the resolution was generally much poorer than Lipeles', twelve lines were sufficiently resolved to be classified as fully resolved by the heretofore mentioned criterion.
Relative Intensities

Table 3 contains the relative intensities of the features in the spectrum produced by 1000 eV helium ions impacting argon. Features arising from a given upper term are listed as a group in order of decreasing wavelength.

For purposes of comparison relative intensities reported by Lipeles for lines arising from the same upper terms are also included in Table 3. It will be noted that Lipeles generally observed more lines from a given upper term than were observed in these experiments. Furthermore, many weakly populated terms which were reported by Lipeles, but not found in this work, are not included in Table 3. The reasons for these differences are as follows. Lipeles was able to detect radiation 100 times weaker than the weakest observed in these experiments. For example, Lipeles was able to detect the 3992 Å line whose intensity was 1000 times less than that of the 4610 Å line; whereas, the weakest line observed in this work, the 3927 Å line, was approximately one-tenth as intense as the 4610 Å line. This difference in sensitivity probably resulted from the presence of an excessive amount of noise during this experiment. The noise was roughly 5 percent of the 4610 Å line's intensity at each beam energy. A much more favorable signal to noise ratio allowed Lipeles to detect many weak lines obscured by the noise in these experiments. Lipeles could also resolve more lines because he could use narrower slits when
A comparison between Lipeles’ findings and the results of this study for 1000 eV He\(^+\) ions impacting on Ar. The intensities are relative measurements normalized to a 4610 Å line intensity of 100 units. An asterisk (*) indicates the lines that were observed during this investigation but were not observed by Lipeles. Each line observed in this work has been classified as fully resolved (R), partially blended (PB) or blended (B) and has been marked accordingly.

<table>
<thead>
<tr>
<th>Upper Terms</th>
<th>Lines, Å</th>
<th>Intensity</th>
<th>Difference In Intensity</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>This Work</td>
<td>Lipeles</td>
<td>This work</td>
</tr>
<tr>
<td>(4p^2p^0) *</td>
<td>6174 R</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>Ar II *</td>
<td>6116 B</td>
<td>23.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5143 B</td>
<td>5142</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>5018 R</td>
<td>17.2</td>
<td></td>
</tr>
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<td></td>
<td>4905</td>
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<td></td>
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<tr>
<td></td>
<td>4639 B</td>
<td>8.0</td>
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<td></td>
<td>4610 R</td>
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<td>100.0</td>
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<tr>
<td>(4p^2D^0)</td>
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<td>1.0</td>
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</tr>
<tr>
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<td>4482 PB</td>
<td>4482</td>
<td>24.3</td>
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<td>This Work</td>
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<td></td>
<td>4728 R</td>
<td>4727</td>
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<tr>
<td></td>
<td>4229 B</td>
<td>4228</td>
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<td>4113</td>
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<td>4659 R</td>
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<td>Intensity</td>
<td>Difference In Intensity</td>
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<tr>
<td>-------------</td>
<td>---------</td>
<td>-----------</td>
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</tr>
<tr>
<td></td>
<td>This Work</td>
<td>Lipeles</td>
<td>This Work</td>
</tr>
<tr>
<td>$5s'2D$ *</td>
<td>4447 B</td>
<td>4337</td>
<td>8.0</td>
</tr>
<tr>
<td>Ar II</td>
<td>4229 B</td>
<td>4227</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>3948 B</td>
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<td></td>
<td>3927 B</td>
<td>3926</td>
<td>6.7</td>
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<td>$4p'4p0$</td>
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<td>5145</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>4430</td>
<td>3992</td>
<td></td>
</tr>
<tr>
<td>$4d'2G$</td>
<td>3560 B</td>
<td>3561</td>
<td>34.0</td>
</tr>
<tr>
<td>Ar II</td>
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<td>23.4</td>
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<tr>
<td>$6s'(\pi)^0$</td>
<td>5881 R</td>
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<td>16.3</td>
</tr>
<tr>
<td>Ar I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^3II_e$ *</td>
<td>5958</td>
<td></td>
<td>7.3</td>
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<tr>
<td>$N_2$</td>
<td></td>
<td></td>
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</tr>
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</table>
scanning the spectrum. Consequently, Lipeles was able to identify many weakly populated upper terms which were undetected during this work.

In the last column of Table 3, intensities of lines which were resolved in this work are compared with those reported by Lipeles for these same lines. The differences were calculated from the following formula,

\[
\text{% Difference} = \frac{\text{Int}_L - \text{Int}_{TW}}{\text{Int}_L} \times 100\%
\]

The agreement between the two sets of intensities is excellent in three cases (6%), fair in two cases (30%), and poor in the remaining two cases (80%). Overall, the agreement is probably as good as could be expected since the minimum error in Lipeles' intensities is 25% and the error in the intensities reported here is at least that large. However, it should be noted that, with one exception, Lipeles' intensities are smaller than the ones measured in these experiments. This could be due, partly or wholly, to the following cause. In this work, lines were considered fully resolved if the blending contributions were less than the constant noise level. Thus blending may have increased significantly the intensities of some weaker lines considered as fully resolved in this work. Lipeles' intensities do not suffer from this defect because his superior resolution insured that blending was negligible for all lines compared in Table 3.
The intensities reported in Table 3 and in Figures 6-10, despite their limited accuracy, show clearly that most of the radiation is produced by transitions of the 4p electron in Ar II from terms having $^2D$ and $^3P$ parent terms. This result is consistent with Lipeles' findings. Ordinarily, it is necessary to consider transition probabilities in order to draw conclusions about populations of upper terms from intensity data. However, because the radiation from the 4p terms of Ar II so greatly exceeds the radiation from all other terms, it is clear that a collision between a helium ion and an argon atom is most likely to produce an argon ion with its outermost electron in the 4p orbital.

**Emission Cross Sections**

Energy dependencies of the emission cross sections of the twelve fully resolved lines in this work are graphically represented in Figures 12-23. The energy dependencies are depicted by straight lines drawn between five widely spaced data points which correspond to the measurements at the different beam energies. Unfortunately, five data points are not sufficient to precisely define an oscillatory structure over such a wide energy range. Nevertheless, the structure is well enough defined to indicate that the energy dependencies of lines from a common upper term exhibit a similar oscillatory structure. This suggests that the levels of the upper term are populated in the same proportions by the collisions at
FIGURE 12. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4072 Å LINE
FIGURE 13. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4132 Å LINE
FIGURE 14. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4278 Å LINE

--- Lipeles' Results

EMISSION CROSS SECTION

BEAM ENERGY ($E_{\text{lab}}$, eV)

1 2 3 4 5

200 400 600 800 1000 1200 1400
FIGURE 15. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4590 Å LINE
FIGURE 16. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4610 Å LINE
FIGURE 17. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4658 Å LINE
FIGURE 18. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4727 Å LINE
FIGURE 19. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4765 Å LINE

--- Lipeles' Results
FIGURE 20. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 4965 Å LINE

BEAM ENERGY ($E_{lab}$, eV)

EMISSION CROSS SECTION

20 16 12 8 4

200 400 600 800 1000 1200 1400
FIGURE 21. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 5017 Å LINE
FIGURE 22. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 5883 Å LINE
FIGURE 23. THE ENERGY DEPENDENCE OF THE EMISSION CROSS SECTION FOR THE 6172 Å LINE
different energies. It will be noted that the energy dependencies of the 4278 Å, 4610 Å, and 4765 Å lines were previously measured by Lipeles for energies of 10 eV to 1000 eV. The energy dependencies of the 4610 Å and 4765 Å lines measured in these experiments connect smoothly onto those of Lipeles as can be seen in Figures 16 and 19, respectively. However, the agreement is not nearly as good for the 4278 Å line in Figure 14. Although the energy dependencies exhibit an identical structure for energies common to both works, the structure observed in this work exhibits oscillations with much smaller amplitudes. It is believed that this is a result of poorer resolution and a less favorable signal to noise ratio.

Lines Not Reported by Lipeles

One of the more interesting results of this investigation was the discovery of four Ar II lines that were not reported by Lipeles. These lines at 4045 Å, 4132 Å, 4447 Å, and 5018 Å were found to belong to terms already known to be populated by the collisions as can be seen in Table 3. Each line was of moderate intensity and should have been easily observed by Lipeles. It is therefore not clear why these lines were not included in his findings.

Several additional features were observed beyond 5200 Å. Upon investigation, these features proved to be an Ar I line, two Ar II lines, and an N₂ band. The Ar II lines, 6116 Å and 6174 Å, arose from the 4p'²F⁰ term and were moderately strong with intensities of 23.2 and 18.0 units,
respectively. The Ar I line, 5881 Å, was also moderately strong with an intensity of 16.3 units. This line is of particular interest since it resulted from direct excitation, whereas the Argon II lines were produced through charge-exchange with simultaneous excitation. Lipkeles mentioned observing several Ar I lines but did not specify them further; only one such line was found in this work. Perhaps the most interesting feature in these spectra is the band produced by the nitrogen impurity in the target gas. The feature's central wavelength was estimated to lie at 5958 Å, but the feature was quite weak with an intensity of 8.0 units which made it difficult to locate the central wavelength precisely. The N₂ band is of special interest for several reasons. Firstly, it was produced through direct excitation as was the Ar I line. Secondly, it was the only feature observed which resulted from collisions between ions and molecules. Lastly, it indicates that the cross section for excitation of N₂ by He⁺ is exceptionally large at low energies since nitrogen was at least ten times less abundant in the interaction region than argon.

**Accomplishment of Purpose**

Results obtained in these experiments show that the atomic beam apparatus has been restored to proper operating condition with two exceptions. Firstly, the apparatus no longer produces a stable beam at energies less than 600 eV. Secondly, the noise level was much higher than in previous
experiments. Unfortunately, no explanation can be given for the low energy beam instability or the excessive noise.

In general, the results of these experiments are in agreement with Lipeles' findings within the limits set by the lower resolution and signal to noise ratio in this work. The four moderately strong Ar II lines observed in this work but not reported by Lipeles constitute the only major differences between the two sets of results. Unfortunately, no explanation can be given as to why these lines were not reported by Lipeles.

For the most part, less information was acquired in extending Lipeles' energy and wavelength ranges than anticipated. Significantly more information would probably have been obtained if the noise level had been lower and if several additional intermediate energies had been analyzed. Nevertheless, it is felt that the ranges of Lipeles' work have been successfully extended to 1500 eV and 6200 Å, respectively.

**Need For Further Study**

On the basis of these limited results, the energy dependencies of lines from a common upper term appear to exhibit a similar structure. If this is true it indicates that the levels of an upper term are populated in the same proportions at different collision energies. This is an interesting possibility whose implications should be explored to determine whether further experimental studies of this
point are desirable. Finally, the intensities of the lines observed in this work should be determined taking polarization into account and compared to theoretically predicted intensity ratios for natural excitation.
APPENDIX I

The purpose of the analysis in this section is to explain the calibration of the optical system and to state the approximations and assumptions which affect the accuracy of the calibration. First, an expression is written for the flux emitted by the filament of the standard lamp. This expression is then modified as the light passes from one optical element to another until, at the photomultiplier where the radiation is converted into a current, an expression is obtained for the current in terms of the filament's radiance.

Assume that the optical system is illuminated by the standard lamp and that the monochromator is set to transmit a wavelength $\lambda_0$. Let the radiance of the standard lamp in a direction which makes an angle $\phi$ with the normal to the filament be represented by $R(\lambda)F(A)\cos\theta$. Here $R(\lambda)$ is the filament's central radiance (photons-cm$^2$-sec$^{-1}$-steradians$^{-1}$-angstroms$^{-1}$) at wavelength $\lambda$ in the direction $\theta=0$, and $F(A)$ is a function which
describes the distribution of the radiance over the filament. Consider the light emitted by an element of area dA at the middle of the filament into the infinitesimal solid angle dω centered about the direction shown in the figure. The flux dφ (photons·sec\(^{-1}\)) in this beam lying within wavelength range dλ at wavelength λ is

\[
dφ = R(λ)\cosθ\delta F(λ)dAdωdλ \quad (1)
\]

Before entering the optical system, this radiation passes through an interference filter of peak transmittance \(t_{\text{if}}\) and through neutral density filters of combined transmittance \(t_{\text{nd}}\). The flux leaving the filters is

\[
dφ = [R(λ)\cosθ\delta F(λ)dAdωdλ](t_{\text{if}}t_{\text{nd}}), \quad (2)
\]

where \(f_{\text{if}}\) is a function which describes the transmittance of the interference filter throughout its band pass. This light passes into the optical system through a quartz window of transmittance \(T\) and is reflected by an ellipsoidal mirror of reflectance \(r_1\) onto the entrance slit of the monochromator. Thus the flux in the infinitesimal beam at the monochromator's entrance slit is

\[
dφ = [R(λ)\cosθ\delta F(λ)dAdωdλ](t_{\text{if}}t_{\text{nd}}f_{\text{if}})(Tr_1). \quad (3)
\]

Since the ellipsoidal mirror overfills the monochromator's entrance slit and angular aperture, the flux collected by the monochromator is obtained by integrating the last equation over the monochromator's angular aperture \(Δω\) and the area \(A\) of the filament which the monochromator views. In performing the integration it is assumed that the angular aperture is sufficiently small so that only the
radiation emitted in a direction nearly normal to the filament ($\cos \theta \approx 1$) lies within the monochromator's angular aperture. Therefore, the flux collected by the monochromator is

$$d\phi \approx [(T_{1}R(\lambda)\tau_{1f}\tau_{n}\tau_{df})d\lambda]d\omega \int_{A} F(\lambda)dA. \quad (4)$$

Light collected by the monochromator is reflected by a spherical collimating mirror of reflectance $r_{2}$ onto a plane diffraction grating whose efficiency is $E$. The light diffracted by the grating then strikes a second mirror of reflectance $r_{3}$ which forms an image of the entrance slit in the plane of the exit slit. Depending upon the amount of overlap between the image and the slit, all or part of the light in the image passes through the exit slit. Thus the flux of wavelength $\lambda$ leaving the monochromator is given by

$$d\phi \approx [(T_{1}r_{2}E_{r_{3}}R(\lambda)\tau_{1f}\tau_{n}\tau_{df})f_{s}d\lambda]d\omega \int_{A} F(\lambda)dA. \quad (5)$$

Here $f_{s}$, called the slit function, is the fraction of the radiation in an image of wavelength $\lambda$ that passes through the exit slit when the monochromator is set to transmit wavelength $\lambda_{0}$.

Upon leaving the monochromator, the radiation strikes a photomultiplier tube and is converted into a current $dJ(\lambda)$. If the overall efficiency of the tube is $S(\lambda)$, the relationship between the current and the flux striking the photocathode is

$$dJ(\lambda) \approx [(T_{1}r_{2}E_{r_{3}}S(\lambda)R(\lambda)\tau_{1f}\tau_{n}\tau_{df})f_{s}d\lambda]d\omega \int_{A} F(\lambda)dA. \quad (6)$$

This equation describes the photomultiplier current produced
by monochromatic radiation of wavelength $\lambda$ emanating from the filament. In order to determine the current produced by all wavelengths of light passing through the exit slit when the monochromator is set at wavelength $\lambda_0$, the previous current must be integrated over the monochromator's band pass $\Delta \lambda$. In performing the integration it is assumed that the band pass is sufficiently narrow to allow the factor $[T_1 r_2 E_3 S(\lambda)]R(\lambda)$ to be replaced by its value at $\lambda_0$. Hence the photomultiplier current produced by all wavelengths of light striking the photocathode when the monochromator is set at $\lambda_0$ is

$$J(\lambda) = [T_1 r_2 E_3 S(\lambda_0)] [R(\lambda_0) t_{if} t_{nd}] \Delta \omega \int_{A} F(A) dA \int_{\lambda_0 - \frac{\Delta \lambda}{2}}^{\lambda_0 + \frac{\Delta \lambda}{2}} f_{if} f_{s} d\lambda. \quad (7)$$

The subscript on the wavelength symbol may be dropped with the understanding that, henceforth, $\lambda$ refers to the wavelength setting of the monochromator.

By letting $K(\lambda) = [T_1 r_2 E_3 S(\lambda)]$

$$C = \Delta \omega \int_{A} F(A) dA \int_{\lambda - \frac{\Delta \lambda}{2}}^{\lambda + \frac{\Delta \lambda}{2}} f_{if} f_{s} d\lambda$$

equation (7) can be written in the simpler form,

$$J(\lambda) \approx K(\lambda) C [t_{if} t_{nd} R(\lambda)] \quad (8)$$
The spectral response of the optical system \( K(\lambda) \) is then related to the photomultiplier current and known quantities by the proportionality,

\[
K(\lambda)C \propto \frac{J(\lambda)}{t_{if} t_{nd} R(\lambda)} \tag{9}
\]

Values of \( K(\lambda)C \) calculated from measured photomultiplier currents using this equation are plotted versus wavelength in Figure 5.

If values of \( K(\lambda)C \) read from Figure 5 are to be used for calculating relative intensities and emission cross sections in a single set of arbitrary units, the proportionality factor \( C \) in equation (9) must be constant. This was assured by performing the calibration in such a way that each quantity in the definition of \( C \) was the same at every point. The monochromator's angular aperture \( \Delta \omega \) was obviously constant. Since the standard lamp was held in one position and the slit width was fixed at 500 microns, the area \( A \) of the filament viewed by the optical system, the monochromator's slit function \( f_s \), and its band pass \( \Delta \lambda \) also were constant. As for the transmittance function \( f_{if} \), all transmittance curves supplied by the maker of the filters had the same shape and base width except the curve for the 3500 Å filter, which was slightly skewed. However, examination of the traces taken during calibration indicated that the effect of the skewed transmittance curve was insignificant, hence \( f_{if} \) was virtually constant. Thus \( C \) was nearly the same at all calibration points, as required.
APPENDIX II

In this appendix an approximate relation will be derived relating the emission cross section of an isolated line to the photomultiplier current produced when the monochromator is set to transmit the peak wavelength $\lambda_0$ of the line.

Consider a small element of the collision volume from which the light of a single spectral line of peak wavelength $\lambda_0$ is emitted. The expression for the flux $d\phi$ emanating from the volume element $dV$ through the solid angle $d\omega$ in the wavelength range $d\lambda$ at wavelength $\lambda$ is

$$d\phi = R(\lambda_0) f(V, \omega, \lambda) dV d\omega d\lambda,$$

where $R(\lambda_0)$ is the peak radiance of the line in (photons cm$^{-2}$ sec$^{-1}$ steradians$^{-1}$ angstroms$^{-1}$) and $f(V, \omega, \lambda)$ is a function which describes the distribution of the flux within the collision volume $V$, throughout space, and across the width of the line. Assuming the distributions are independent of one another, the previous expression can be rewritten as

$$d\phi = R(\lambda_0) [f(v) dv \times f(\omega) d\omega \times f(\lambda) d\lambda],$$

where the function $f(\lambda)$ is called the line shape. This
radiation passes through a quartz window of transmittance \( T \) and is reflected by an ellipsoidal mirror of reflectance \( r_1 \) onto the entrance slit of the monochromator. Thus the flux at the entrance slit of the monochromator is given by

\[
d\phi = (T r_1) R(\lambda_0)[f(\nu) d\nu \times f(\omega) d\omega \times f(\lambda) d\lambda]. \tag{3}
\]

Since the ellipsoidal mirror overfills the monochromator's entrance slit and angular aperture, the effective flux of wavelength \( \lambda \) collected by the monochromator is obtained by integrating the last equation over the monochromator's angular aperture \( \Delta \omega \) and the portion \( V' \) of the collision volume which the monochromator views. The result is

\[
d\phi = (T r_1) R(\lambda_0) f(\lambda) d\lambda \int_{\Delta \omega} f(\omega) d\omega \int_{V'} f(V) dV. \tag{4}
\]

Light collected by the monochromator is reflected by a spherical collimating mirror of reflectance \( r_2 \) onto a plane diffraction grating whose efficiency is \( E \). The light diffracted by the grating then strikes a second mirror of reflectance \( r_3 \) which forms an image of the entrance slit in the plane of the exit slit. All or part of the light in the image passes through the exit slit depending upon the amount of overlap between the image and the exit slit. Thus the flux of wavelength \( \lambda \) leaving the monochromator is given by

\[
d\phi = (T r_1 r_2 E r_3) R(\lambda_0) f_s f(\lambda) d\lambda \int_{\Delta \omega} f(\omega) d\omega \int_{V'} f(V) dV. \tag{5}
\]

Here \( f_s \), called the slit function, is the fraction of the
radiation in an image of wavelength $\lambda$ that passes through the exit slit when the monochromator is set to transmit wavelength $\lambda_0$.

Upon leaving the monochromator, the radiation strikes a photomultiplier tube and is converted into a current $dJ(\lambda)$. If the overall efficiency of the tube is $S(\lambda)$, the relationship between the current and the flux striking the photocathode is

$$dJ(\lambda) = \left[ Tr_{12} Er_3 S(\lambda) \right] R(\lambda) \int f(\omega) d\omega \int f(V) dV.$$  

This equation describes the photomultiplier current produced by monochromatic radiation of wavelength $\lambda$ emanating from the collision volume. In order to determine the current produced by all wavelengths of light passing through the exit slit, the previous photomultiplier current must be integrated over the monochromator's band pass $\Delta \lambda$. In performing the integration it is assumed that the band pass is sufficiently narrow to allow the factor $\left[ Tr_{12} Er_3 S(\lambda) \right]$ to be replaced by its value at $\lambda_0$. Hence the photomultiplier current produced by all wavelengths of light striking the photocathode when the monochromator is set at $\lambda_0$ is

$$J(\lambda_0) = \left[ Tr_{12} Er_3 S(\lambda_0) \right] R(\lambda_0) \int_{\lambda_0 - \Delta \lambda/2}^{\lambda_0 + \Delta \lambda/2} f(\omega) d\omega \int_{V'} f(V) dV \int f_\lambda f(\lambda) d\lambda.$$  

The subscript on the wavelength symbol may be dropped with the understanding that, henceforth, $\lambda$ refers to the wavelength setting of the monochromator.
By letting

$$K(\lambda) = \left[ \text{Tr} \frac{1}{r_2} Fr_3 \delta(\lambda) \right]$$

and

$$g(\Delta \omega)g(V')g(\Delta \lambda) = \int_{\Delta \omega} f(\omega) d\omega \int_{V'} f(V) dV \int_{\lambda - \frac{\Delta \lambda}{2}}^{\lambda + \frac{\Delta \lambda}{2}} f_s f(\lambda) d\lambda$$

the photomultiplier current can be expressed simply as

$$J(\lambda) = K(\lambda)g(\Delta \omega)g(V')g(\Delta \lambda)R(\lambda). \quad (8)$$

The previous expression relates the photomultiplier current to the flux collected by the optical system, but the total flux produced by the collisions is

$$\phi(\lambda)_{\text{Total}} = R(\lambda) \int_{0}^{\infty} f(\omega) d\omega \int_{V} f(V) dV \int_{-\infty}^{+\infty} f(\lambda) d\lambda, \quad (9)$$

where the limits of integration are taken over the collision volume $V$ and the width of the spectral line. The last equation can be written as

$$\phi(\lambda)_{\text{Total}} = R(\lambda)G_\omega G(V)G_\lambda, \quad (10)$$

where the $G$ factors represent the definite integrals in equation (9). By solving for the radiance $R(\lambda)$ in equation (8) and inserting the result into equation (10), an expression for the total flux in terms of the photomultiplier current is obtained. This expression is

$$\phi(\lambda)_{\text{Total}} = \frac{J(\lambda)G_\omega G(V)G_\lambda}{K(\lambda)g(\Delta \omega)g(V')g(\Delta \lambda)} \quad (11)$$

The total flux can be related to the emission cross section by calculating the excitation produced in collisions.
between beam ions and target gas molecules. If the target
gas density is very low, as it was in these experiments, the
beam is not attenuated appreciably in traversing the
collision volume, and the number of secondary collisions is
negligible. Under these conditions the total flux is given
approximately by

\[ \phi(\lambda)_{\text{Total}} \approx \bar{I} \bar{N} \zeta(\lambda) \]  

(12)

where \( \bar{I} \) is the mean beam current, \( \bar{N} \) is the mean target gas
density, and \( L \) is the length of the collision volume.

By equating the two previous expressions for the total
flux (equations 11 and 12), an expression for the emission
cross section is obtained in terms of the photomultiplier
current. This expression is

\[ \zeta(\lambda)_{\text{Total}} = \left[ \frac{J(\lambda)}{\bar{I} \bar{N}} \right] \left[ \frac{G_\omega G(V) G(\lambda)}{K(\lambda) g(\Delta \omega) g(V') g(\Delta \lambda)} \right] \]  

(13)

If the right hand side of this equation is multiplied by
\((C/C)\), where \( C \) is the proportionality factor in equation (9)
of Appendix I, the result is

\[ \zeta(\lambda) = \left[ \frac{J(\lambda)}{\bar{I} \bar{N}} \right] \left[ \frac{C G_\omega G(V)}{K(\lambda) C g(\Delta \omega) g(\Delta \lambda) g(V') L} \right] \]  

(14)

But the ratio \( g(V')/G(V) \) equals \( F \), the fraction of collision
light from the image of the collision volume which passes
into the monochromator when the slit width is less than
2000 microns. Furthermore, it can be shown that \( G(\lambda) \approx g(\Delta \lambda) \)
when the line width \( \delta \lambda \) is much narrower than the mono-
chromator's band pass. In order to demonstrate this, let
us approximate the slit function \( f_s \) and the line shape \( f(\lambda) \)
by the triangular distributions below.

Since $f(\lambda)$ is symmetric about the central wavelength $\lambda$ and is zero beyond the edges of the triangle, $G\lambda$ is given by

$$G\lambda = 2 \int_0^{\delta\lambda/2} f(\lambda) d\lambda$$  \hspace{1cm} (15)$$

$$G\lambda = 2 \int_0^{\delta\lambda/2} [1 - \left(\frac{2}{\delta\lambda}\right)\lambda] d\lambda$$  \hspace{1cm} (16)$$

$$G\lambda = \frac{\delta\lambda}{2}$$  \hspace{1cm} (17)$$

Because $f(\lambda)$ is narrower than $f_s$, the factor $g(\Delta\lambda)$ is given by

$$g(\Delta\lambda) = 2 \int_0^{\delta\lambda/2} f(\lambda)f_s d\lambda$$  \hspace{1cm} (18)$$

$$g(\Delta\lambda) = 2 \int_0^{\delta\lambda/2} [1 - \left(\frac{2}{\delta\lambda}\right)\lambda][1 - \left(\frac{2}{\Delta\lambda}\right)\lambda] d\lambda$$  \hspace{1cm} (19)$$

$$g(\Delta\lambda) = \frac{\delta\lambda}{2}\left[1 - \frac{1}{3} \frac{\delta\lambda}{\Delta\lambda}\right]$$  \hspace{1cm} (20)$$

Since in these experiments the line shapes are determined principally by Doppler broadening, the base widths $\delta\lambda$ of the assumed triangular shapes can be approximated by twice the Doppler widths at half maximum. Hypothetical lines at
the limits of the experimental range, 3500 Å to 6200 Å, have
Doppler widths at half maximum of $8.6 \times 10^{-3}$ Å and
$1.5 \times 10^{-2}$ Å, respectively. The smallest band pass $\Delta \lambda$
was 5.2 Å obtained with 100 micron slits. Thus the largest
value of the second term in the brackets on the right hand
side of equation (20) is

$$\frac{1}{3} \frac{\delta \lambda}{\Delta \lambda} \approx 2 \times 10^{-3}$$

This term may be ignored in comparison to the first term
in the brackets of equation (20), hence $g(\Delta \lambda)$ in these
experiments is very nearly equal to $\delta \lambda/2$. Consequently,
the factors $G_\lambda$ and $g(\Delta \lambda)$ cancel from equation (14), which
becomes

$$\xi(\lambda) \approx \left[ \frac{J(\lambda)}{I \cdot N} \right] \left[ \frac{1}{F \cdot K(\lambda) C} \right] \left[ \frac{C \omega}{g(\Delta \omega) L} \right]. \quad (21)$$

The ratio $G_\omega/g(\Delta \omega)$ in the last equation depends upon
the polarization of the light produced by the transition in
question. When excitation conditions are anisotropic, as
in these experiments, the light in any given line is
generally polarized, its spatial distribution is anisotropic,
and the distribution is related to the polarization. From
the results of Percival and Seaton,\textsuperscript{14} one concludes that

$$\frac{f(\omega)}{G_\omega} = \frac{3(1 - P\cos^2 \alpha)}{4\pi(3-P)} \quad (22)$$

where $P$ is the fractional polarization of the light and $\alpha$ is
the angle between the ion beam axis and the direction in
which the light is viewed. $P$ is defined in terms of $I_\parallel$ and
$I_\perp$, the radiant intensities (photons-sec$^{-1}$-steradians$^{-1}$)
that are observed to be polarized parallel and perpendicular to the beam axis when the light is viewed normal to that axis.

\[ P = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp} \]

In these experiments the optical axis is perpendicular to the beam, and the monochromator's angular aperture is sufficiently small so that \( \cos \theta \approx 0 \) for all directions lying within the aperture. Consequently, integration of equation (22) over the aperture yields

\[ \frac{G_\omega}{g(\Delta \omega)} \approx \frac{4\pi(3-P)}{3\Delta \omega} \]  \hspace{1cm} (23)

Upon substituting this result into equation (21), one obtains

\[ \zeta(\lambda) \approx \left[ \frac{J(\lambda)}{I \cdot N} \right] \left[ \frac{1}{F \cdot K(\lambda) \cdot C} \right] \left[ \frac{4\pi(3-P)}{3\Delta \omega L} \right] \]  \hspace{1cm} (24)

In analyzing the results of these experiments, polarization was neglected, i.e., \( P = 0 \). Therefore the previous equation becomes

\[ \text{CONSTANT} \times \zeta(\lambda) = \left[ \frac{J(\lambda)}{F \cdot K(\lambda) \cdot C \cdot I \cdot N} \right] \]  \hspace{1cm} (25)

In order to determine the possible error introduced into the relative intensities and emission cross sections by neglect of polarization, the extreme cases in which \( P = 0 \) and \( P = 1 \) must be compared. When this is done, the maximum possible error in the cross sections is found to be 50%. As regards the relative intensities, neglect of the polarization
gives the values reported in this work a special meaning, i.e., they are the relative intensities of the light entering the monochromator, not necessarily the relative intensities of light emitted from the collision volume. When referred to the collision volume, these relative intensities, like the emission cross sections, may be in error by as much as 50%.
REFERENCES


