Vacuum-ultra-violet polarization studies following electron impact excitation.

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VACUUM-ULTRA-VIOLET POLARIZATION
STUDIES FOLLOWING
ELECTRON IMPACT EXCITATION

by

William Leslie Karras.

A Thesis
submitted to the
Faculty of Graduate Studies and Research
Through the Department of
Physics in Partial Fulfillment
of the Requirements for the Degree
of Master of Science at
the University of Windsor

Windsor, Ontario, Canada
1988
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ABSTRACT

The polarization of vacuum ultra violet radiation emitted following electron impact on a variety of gaseous targets has been of investigated in detail. This information can be useful as a secondary standard for absolute calibration of equipment which is polarization sensitive in the V.U.V., and for normalizing information collected using electron-photon coincidence techniques. In addition, polarization data can be used to calculate the relative cross sections of states within an unresolved multiplet.

A crossed electron-gas beam system has been used in conjunction with a single reflection, gold surfaced, polarization analyzer. Using a computer-automated system and calibration values collected with a four mirror polarizer, we were able to accurately determine the polarization of the radiation from He, He⁺, Ne, Ar, Kr, Xe, H₂ and N₂ as a function of electron impact energy continuously from threshold to 500 eV.

Previous measurements of the polarization have been confirmed and extended. Threshold values have been compared with the predictions of angular momentum arguments. Some effect, in addition to negative ion resonances, is depolarizing the radiation above threshold. (This may be
accounted for by the electron correlation scheme proposed by Heideman et. al.) Comparisons with the predictions of Heddle et. al. concerning the energy region where $P$ changes sign have also been examined. The best agreement between experiment and theory at high energy ($>100$ eV) is the Born approximation.
To Tana

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The data collection period for this experiment, excluding diagnostics, exceeded 3000 hours, with a mean time between failure of well over 200 hours. Such impressive numbers would not have been possible without the dedication to quality displayed by the technical staff at the University of Windsor Physics Department. In particular, I would like to sincerely thank Mr. W. Grewe of the machine shop and Mr. B. Masse of the electronics shop for their efforts.

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I. INTRODUCTION

The polarization of radiation emitted as a result of electron impact has been the object of investigation for many years\(^1\). The development of secondary standards for absolute calibration in the vacuum ultra-violet (V.U.V.) region of the spectrum has created a demand for accurate information\(^2,3,4\). As well, current electron-photon coincidence techniques, in which polarization correlation functions are measured to allow the extraction of the fine details of the excitation processes, can make use of linear and circular polarization information to calibrate results\(^4,5,6,7\). Also, polarization data can be used to correct electron impact excitation functions for detector polarization sensitivity, and for the calculation of relative cross sections within an unresolved multiplet\(^8\).

Polarization measurements taken in the V.U.V. region are difficult to perform as many practical experimental problems exist. Data presented on helium by various groups contain considerable scatter. As well, many other gases have not, as yet, been investigated. Therefore, we have endeavoured to provide the initial entries to a polarization data bank for V.U.V. radiation. The polarization of integrated radiation from He, He\(^+\), Ne, Ar\(^9\),
-Kr, Xe, H₂, and N₂ has been investigated from threshold to 500 eV impact energy. Particular attention has been paid to the polarization at threshold, the energy at which the polarization is zero, and the slope of the polarization at this energy. (See later)
II. REVIEW OF PREVIOUS WORK

Several techniques exist for measuring the polarization of light emitted following electron impact. In the visible region of the spectrum, transmission optics can be used. In the V.U.V. however, reflection optics must be used, as normally transmissive materials readily absorb short wavelengths. When unpolarized light of any wavelength is reflected from a metal surface, it becomes partially plane polarized. Using this principle, reflection polarization analyzers can be constructed to measure the fractional polarization of incident light. The polarization efficiency of the mirror is dependent on the material of the mirror, and the angle of incidence and wavelength of the incident light. In many cases, the appropriate reflection properties of a material are not well documented. This leads to a problem in calibrating results.

One technique used to overcome this problem is to measure the angular distribution of the radiation. This technique was apparently first used by Smit\(^9\), with visible light, and since has been extended into the V.U.V. by others\(^10,11\). The polarization is given by:
\[ P = \frac{I_{\|} - I_{\perp}}{I_{\|} + I_{\perp}} \]  

where \( I_{\|} \) and \( I_{\perp} \) are the intensities of the radiation per unit solid angle emitted perpendicular to the exciting electron beam, whose electric vectors are aligned parallel and perpendicular respectively to the quantization axis. The intensity as a function of angle for electric dipole radiation is given by:

\[ I(\theta) = I_{\|} \sin^2 \theta + I_{\perp} \left(1 + \cos^2 \theta\right) \]  

Where \( \theta \) is the angle measured from the quantization axis. Combining eqs. (1) and (2) and simplifying, we get:

\[ I(\theta) = (I_{\|} + I_{\perp}) \left(1 - P \cos^2 \theta\right) \]  

Since \( I_{\|} + I_{\perp} \) is the total intensity measured normal to the electron beam, we see that:

\[ I(\theta) = I(90^\circ)(1 - P \cos^2 \theta) \]

If one experimentally measured the angular distribution of the radiation, the polarization could then be determined. This method lacks the calibration problems inherent with other methods but it does introduce practical experimental problems which lead to a significant uncertainty in the results.
One can also accept the limitations of the known reflection coefficients and proceed to measure the polarization. The detector is mounted to observe the interaction region along an axis normal to the electron beam. The detector can then be rotated about this axis to directly measure the intensity of photons whose electric vector is parallel and perpendicular to the electron beam, respectively. The polarization can then be calculated using:

\[ P = \eta \left[ \frac{I^m - I^{m'}}{I^m + I^{m'}} \right] \]  

where \( I^m \) and \( I^{m'} \) are the measured intensities of radiation whose electric vector is parallel and perpendicular to the quantization axis and \( \eta \) is the polarization efficiency which is calculated from the reflection coefficients of the material. Considerable care must be taken in calibrating the results. Much information, including the present work, is obtained using this method.

Another method used to measure V.U.V. polarization is the use of electron-photon coincidence techniques\(^{13,14}\). This method is similar to reflection analyzer techniques but makes use of coincidence gating to select specific transitions. The information collected in this manner,
however is not directly comparable to reflection measurements, as it is dependent on the relative differential cross sections, rather than the relative integral cross sections. This method has the advantage of measuring the polarization of a single transition, but it is impractical for use in measuring polarizations over a wide energy range, as the count rates are extremely low.

Previous V.U.V. measurements of the polarization of atomic radiation following electron impact are very limited and available only for helium$^{11,13,14,15}$, with some work in argon$^{16}$, nitrogen$^{17}$, and hydrogen.$^{18}$ In helium there is considerable disagreement among these measurements. Calculations suggest$^{19}$ that the polarization should be virtually independent of the principal quantum number, $n$. Therefore we have included, in our survey, the results of measurements taken in the visible region ($n^{1}P-2^{1}S$) of helium. (See Fig. 13 and reference (14)).

It is interesting to note that, if desired, polarization effects can be eliminated from an experiment. Assuming dipole radiation, the angular intensity distribution is given by:

$$I(\theta) = \frac{I}{4\pi} \left[ \frac{3(1 - P\cos^2 \theta)}{3 - P} \right]$$

(6)
where \( I \) is the total intensity of the emitted radiation. If we let:

\[
\cos^2 \theta \sim \frac{1}{3}
\]  

(7)

then we have:

\[
I(54.5^\circ) = \frac{I}{4\pi}
\]  

(8)

and the measured intensity is independent of polarization. This is the so-called "magic" angle of observation.
III. THEORY

The theoretical basis for the polarization of atomic line radiation, following electron impact, was established by Percival and Seaton\textsuperscript{20}. Their argument was based on four assumptions:

- Three atomic energy levels are distinguished: an initial level "a" (usually the ground level), an excited level "b" which is populated after collision, and a final level "c" which is reached after photon emission.

- The experimental conditions are such that there is a completely isotropic distribution of spin directions in the incident electron beam, and in the initial state of the atom.

- The initial state of the atom has zero angular momentum. Consequently the anisotropy of the emitted radiation can be considered to be the direct result of the interaction of the incident electron.

- Total spin and total orbital angular momentum are separately conserved throughout the interaction.
Using these assumptions, the threshold polarization can be calculated. Spin, orbital angular momentum and its component in the quantization direction are all separately conserved and the atom is presumed to be initially without angular momentum. At threshold, because the incident electron is travelling in the z-direction it clearly has $m_z=0$. The scattered electron has no kinetic energy and as a result no angular momentum. Therefore the $z$-component of angular momentum of the excited state ($M_z \hbar$) must be zero because the $z$-component of angular momentum of both the incident and scattered electrons is zero. Thus, only states with $M_z=0$ can be excited. The threshold polarization can then be calculated, without a detailed knowledge of the cross sections of the orbital angular momentum states.

We first consider the polarization for a given impact energy. The polarization is given by:

$$P = \frac{K_z - K_x}{K_z + K_x}$$

(9)

where $K_z(K_x)$ is the rate of emission of photons whose electric vector is parallel to the $x$ ($z$) direction. $z$ is considered to be the axis of quantization (defined by the electron beam).

Clearly:
\[ K = K_x + K_y + K_z \]  
\[ (10) \]

and since there is symmetry about the \( z \)-axis, \( K_x = K_y \). Then

\[ K = 2K_x + K_z \]  
\[ (11) \]

From eqs. (9) and (11) it can be seen that:

\[ P = \frac{3K_z - K}{K_z + K} \]  
\[ (12) \]

Percival and Seaton derived the following relation for \( K_i \), where \( i = x, y, z \):

\[ K_i = \frac{v_b C(v_{bc})}{A^2 W_a} \sum_{a,y} \left| \sum_{\beta} (\gamma \mid i \mid \beta) \bar{F}(\beta) f_{\beta}(a \vec{R}_a | \vec{R}) \right|^2 \, dw(\vec{R}) \]  
\[ (13) \]

where \( v_b \) is the velocity of electrons incident on atoms in level \( b \), \( 1/\lambda \) is the radiative lifetime of the state, \( W_a \) is the statistical weight of level \( a \), \( \vec{R} \) is the wave vector of the scattered electron lying within the solid angle \( dw(\vec{R}) \), and \( f_{\gamma}(a \vec{R}_a | \vec{R}) \) is the scattering amplitude for excitation of level \( b \) from level \( a \). The symbols \( a, \beta, \gamma \) represent the quantum numbers of state \( a, b, \) and \( c \) respectively. Also:

\[ C(v_{bc}) = \frac{64 \pi^4 e^2 v_{bc}^3}{3 \hbar c^3} \]  
\[ (14) \]

and \( h v_{bc} = E_b - E_c \). \( f \) is a unit complex vector satisfying:
\[ F'(\beta^*) \cdot F(\beta) = \frac{A}{2\pi i \nu_{\beta\beta^*} + A} \] (15)

where \( \beta \) and \( \beta^* \) are two states of \( b \). This allows the polarization to be calculated at any energy using eq. (12).

Blum\textsuperscript{21} gives the following expression for the threshold polarization:

\[ P_t = \frac{\left( \frac{15}{2} \right)^{1/2} (-1)^{l_2} G(l)^2 \begin{pmatrix} 1 & 1 & 2 \\ L & L & L_2 \end{pmatrix} \begin{pmatrix} L & L & 2 \\ 0 & 0 & 0 \end{pmatrix}}{\gamma^2 + \left( \frac{3}{4} \right)^{1/2} (-1)^{l_2} G(l)^2 \begin{pmatrix} 1 & 1 & 2 \\ L & L & L_2 \end{pmatrix} \begin{pmatrix} -L & L & 2 \\ 0 & 0 & 0 \end{pmatrix}} \] (16)

where \( L \) and \( L_2 \) represent the orbital angular momentum of the upper and lower states of the observed decay, \( \gamma \) is the life-time of the state in question and \( G(l) \) is a perturbation co-efficient which accounts for fine and/or hyperfine depolarization effects and can be obtained from:

\[ G(l)^k = \frac{1}{(2S+1)(2l+1)} \sum_{J,J_F,F} (2J+1)(2J^*+1)(2F^*+1)(2F+1) \]

\[ \begin{pmatrix} J^* & F^* & I^* \\ F & J & K \end{pmatrix} \begin{pmatrix} L & J^* & S \end{pmatrix} \begin{pmatrix} \exp \left[ \frac{i(E_{1'} - E_1)2\pi t}{\hbar} + \frac{(\gamma_{1'} + \gamma_1)t}{2} \right] \end{pmatrix} \]

where \( S \) is the spin quantum number, \( I \) is the nuclear spin quantum number, \( J \) and \( J' \) are the angular momentum quantum numbers of the upper and lower states of the transition.
respectively, $F$ and $F'$ are the appropriate total angular momentum quantum numbers, $\kappa$ is the quantum number resulting from the interaction of $J$ and $J'$, $E$ and $E'$ are the energies of the initial and final states and $1/\gamma$, $1/\gamma'$ are lifetimes of the states. For the threshold situation the scattered electron has zero energy and hence zero angular momentum. Therefore the magnetic quantum number of the excited atom cannot change. If both fine and hyperfine splittings are larger than the line width and if the observation time is long compared to the lifetime, the time dependent part of $G(t)$, drops out. We then have:

$$\theta(L) = \frac{1}{\gamma(2S+1)(2I+1)} \frac{1}{3} (2J+1)(2F+1)^2 \{ J F \ 1 \}^2 \{ I F \ 2 \} \{ S J \ 2 \}$$

(18)

An expression involving the threshold polarization, $P_\parallel$, of a neutral atom was derived by Heddle$^{22}$, within the framework of the Bethe approximation. Consider the expression for the polarization proposed by Bethe$^{23}$:

$$P = \frac{P_\parallel (3 \cos^2 \chi - 1)}{2 - P_\parallel (1 - \cos^2 \chi)}$$

(19)

Where $\chi$ is the angle between the quantization direction and the momentum transfer. McFarlane$^{24}$ has shown that for an optically allowed transition;
\[
\cos^2 x = \left[ \ln \left( 4c_i \frac{E_s}{R} \right) \right]^{-1}
\]

(20)

Where \( E_s \) is the energy of the incident electron, \( R \) is the Rydberg constant, and \( c_i \) accounts for the angular distribution of the excitation cross section, and can be determined either directly from theory or experimentally with the use of a Fano plot of the emission cross section versus electron energy. Fano\textsuperscript{25} has shown that the excitation cross section of an optically allowed transition can be represented by:

\[
Q = \frac{A}{E_s} \ln \left( 4c_i \frac{E_s}{R} \right)
\]

(21)

where \( Q \) is the relative intensity (or cross section) of the observed emission and \( A \) is a constant. Thus a plot of \(QE_s\) versus \( \ln(E_s) \) for experimental data should, at high energies, approach a straight line, which cuts the energy axis at:

\[
E_{s*} = E_o = \frac{R}{4c_i}
\]

(22)

and \( c_i \) can be determined.

Heddle\textsuperscript{26} also shows that the energy, \( E_s \), where the polarization intersects the abscissa is given by:
\[ E_P = a^2 E_o \]  

Combining eqs. (19), (20), and (22) and taking the derivative of \( P \) with respect to \( \ln(E) \) at \( E_r \), Heddle shows that for an optically allowed excitation process:

\[ \frac{dP}{d(\ln E_o)} \bigg|_{E_r} = \frac{-P_r}{6 - 2P_r} = G' \]

where \( G' \) is the slope of the \( P \) versus \( \ln(E) \) curve at \( E = E_r \).

Heddle has shown that if there is a significant unpolarized cascade contribution to the emitted radiation then eq. (24) can be modified to:

\[ G'(1 + \beta) = \frac{-P_r}{6 - 2P_r} \]

where \( \beta \) is the cascade component of the observed radiation.

If an optically forbidden excitation process is considered then eq. (25a) must be modified to:

\[ G'_{r}(1 + \beta) = \frac{-3P_r}{6 - 2P_r} \]  

(25b)
IV. APPARATUS AND PROCEDURE

A schematic representation of our experimental setup is shown in fig 1. An approximately monoenergetic electron beam was crossed with an atomic or molecular gas beam. In an adjoining, differentially pumped chamber, detection of the resultant vacuum ultra-violet (V.U.V.) fluorescence photons was accomplished with a single or multi-mirror reflection polarization analyzer. The in-house built analyzer contained a gold coated mirror which was inclined to the path of the photons, at an angle (57.5°) which optimised the selection of a given linear polarization. The reflected photons were then detected by a channel-electron multiplier. It was possible to rotate the polarization analyzer around the axis defined by the fluorescence photons. By measuring the flux of photons, whose electric vector was oriented parallel to the electron beam, and comparing it to the measured flux of those with electric vectors oriented perpendicular to the electron beam, we were able to determine the fractional polarization of the incident light.
Figure 1: Schematic diagram of the apparatus.
IV. 1 THE GASES

Each gas used was of research grade purity and was vented from the bottle using an ultra-pure regulator. Prior to its entrance into the interaction area, the gas being studied passed through a copper coil. For He, He⁺, Ne, H₂, and N₂ the coil was immersed in low temperature liquid nitrogen to capture impurities, such as water, on the gas line walls. The gas was then emitted into the interaction region through a 1.6 cm long hypodermic needle. The needle was coated with carbon soot, to prevent electron or photon reflections, and its aperture was placed 3 mm from the center of the electron beam. The pressure of the gas behind the needle was between 30 and 100 mtorr, which corresponded to a change in chamber pressure of about $1.0 \times 10^{-7}$ torr. Measurements were made to ensure that in this pressure region, the measured intensity of radiation was proportional to the pressure, and the polarization was independent of pressure.
IV. 2 THE ELECTRON GUN

The electron gun was specifically designed by Dr. Peter Hammond, to obtain good collimation and constant current over a wide impact energy range. We required a current of about 25\(\mu\)A with an impact energy range of 10 to 500 eV. Other design considerations included strict space limitations and good beam characteristics in the interaction region.

The electrons were produced by thermionic emission from an electrically heated thoriated tungsten filament. The electrons were removed from the filament using a Pierce diode arrangement (Fig. 2) and accelerated to a positively charged defining aperture. A second skimming aperture was placed in the path of the beam to remove excessively divergent electrons.

The beam was focussed by one of three, three-element lens stacks. Five equally spaced lens elements (Fig. 2) were used and the three individual lenses were obtained by using the first, the middle or the last three lens elements respectively. When not involved in the lens being used, an element was held at the potential of its nearest neighbor. Thus it became part of an equipotential region. Each stack was positioned for optimum focussing of a
Figure 2: A 1:1 scale representation of the electron gun, hypodermic needle, and Faraday Cup. Voltages listed for the electron gun are with reference to Target plus impact energy (Monochromator Earth). Target is real earth. The Faraday cup end voltage is with reference to the Target.
specific impact energy range. The first stack was designed as a decelerating lens for use with impact energies ranging from 5.5-12.5 eV. The focussing element was placed 3.5D from the first aperture, where D was the diameter of the aperture of the lens, (7.6mm).

The second lens stack was placed 4.0D from the first aperture and was designed to be used as an Einzel lens. We could control impact energies from about 42 to 58 eV with this configuration. The third lens stack was designed as an accelerating lens, for use with impact energies from 180 to 440 eV and was placed 4.5D from the first aperture.

In practice, only the last lens group was used for the entire energy range of the gun. This was due to the impracticality of switching lens stacks during a data collection period, and the difficulty in ramping lens voltages non-linearly with respect to impact energy. With a single focussing element, we could not hope to focus the electron beam in the interaction region for all impact energies, but we could ensure adequate collimation throughout our required energy range.

Figure 3 shows the electron gun circuit. The thoriated tungsten filament used measured .005" in diameter and was heated with a direct current of about 2.3 A. The Pierce element of the gun was maintained at about -11 V. The anode,
Figure 3: Schematic diagram of the experimental circuitry: FCE refers to the Faraday Cup end; IR refers to the elements of the electron gun; GE is the "Grid Earth" or the electron gun filament housing bias; CE refers to the channeltron Entrance.
with its 1mm defining aperture, was biased to +200V to maintain sufficient collimation of the beam, and provide adequate current. All lenses and apertures were made from .003" thick molybdenum plates, and separated by machinable fibre-glass (MACOR) spacers. The second aperture, also 1mm in diameter, was wired to the first element of the lens stack. The distance between each adjacent lens element was 1/2 of the distance D.

Since a single lens stack was used, we required detailed information regarding various lens voltage effects on the electron beam for the entire impact energy range. For this purpose, a computer program was written by Dr. Hammond, which made use of the information published by Harting and Read. We required a stable image position, far from the skimming aperture of the gun, to provide good collimation and sufficient magnification in the interaction region. Calculations suggested an 80 V bias for use on the focussing lens, this being the best compromise of beam characteristics. Figure 4 and Table 1 show the electron beam properties over the required impact energy range. Calculations estimate a beam energy width of about 500 meV at 20 eV impact energy.

The entire gun was shielded from the interaction region by an earthed copper cylinder. The last lens element, as
Figure 4: A plot of electron beam magnification as a function of electron energy in the interaction region. A magnification of 1 represents an electron beam diameter of 1.5mm. A negative magnification represents an inverted beam. (See Table 1 for details.)
Electron Beam Magnification
(as a Function of Electron Energy)
Table 1: Electron Gun and Beam Characteristics:

$V_3$ is the voltage applied to the last lens element with respect to "monochromator earth". (This is essentially equivalent to the electron energy.); $f_1$, and $f_2$ are the focal lengths from the first and second focal planes, respectively. $F_1$, and $F_2$, represent the location of the focal points, measured from the center lens element; $Q$ is the image position, measured from the center lens element; and $M$ is the magnification of the electron beam in the interaction region.
### Table 1: Electron Gun and Beam Characteristics

Diameter of Lens Apertures: \( D = 7.6 \text{ mm} \)

Separation of Lens Apertures: \( A = 0.5D \)

Object Length: \( P = 4.5D \)

Bias of First Lens Element: \( V_1 = 200V \)

Bias of Second Lens Element: \( V_2 = 80V \)

Bias of Third Lens Element: \( V_3 = 0-500V \)

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well as the exposed surface of the shielding, was coated with carbon soot to minimize electron or photon reflections.

The faraday cup (Fig. 2) was 9mm in diameter and located 2.5 cm from the end of the gun and 1.1 cm from the interaction region. The electrically isolated faraday cup end was biased to +25 V with respect to the main body in order to prevent escape of reflected or secondary electrons. A typical current falling on the cup was between 25 and 30 μA. The end collected 60% of the total current at low energies and this increased to 100% above 40 eV. This was a further indication of the good focussing performance of the gun.

Stray magnetic fields, in the region of the electron beam were limited to less than 50 mG, with a conetic shield that surrounded the interaction area.

The intensity of the fluorescence photons was found to be directly proportional to the electron beam current. This was an indication of the good beam characteristics of the electron gun.

IV. 3 DETECTION SYSTEM

Photons from the interaction region passed through a 9 mm aperture that was 20 cm away in an adjoining chamber.
This aperture had a deflector plate maintained at +50 V to deflect stray electrons. The photons then traveled another 15 cm to the polarization analyzer (Fig. 5). (The detection chamber was pumped with a turbo-molecular pump to minimize trapping of rösonance radiation in this region.) Calculations suggest that, although the total path length is large, the radiation absorbed, re-emitted, and then detected constituted less than 0.005% of the total radiation detected.

Inclined at 57.5° to the path of the incoming photons was a one inch diameter, optically flat, gold coated pyrex mirror, (Janos Optical). The mirror preferentially reflected photons of a given polarization into a channel-electron multiplier, (Galileo Electro-Optics 4039) where they were detected, (The detection efficiency of the channeltron as a function of wavelength is shown in Fig. 6). To prevent the condensation of outgassed materials on the mirror, and thus changing its reflection properties, the polarizer was maintained at 70° C. This was accomplished with the use of a current carrying resistance wire, encased in a four hole ceramic tube, and placed in a hole that was bored in the polarizer. The temperature was monitored with a copper-constantan thermocouple, mounted on
Errata: Page 32 is missing due to an error in pagination.
Figure 5: A schematic diagram of the polarization analyzer. Reflectors are gold-coated optically flat mirrors. The first three mirrors were removed for all but the calibration measurements. The analyzer was rotated about the axis defined by the incoming photons.
Figure 6: A plot of channeltron efficiency as a function of wavelength: + represents the channeltron efficiency with no coating; x represents the efficiency with a CsI coating. All measurements observing principal wavelengths above 100.0 nm were taken with a coated channeltron. These values were derived from the work of Johnson et al. 42
the top of the polarizer.

It was found that during collection, photoelectrons were being emitted from the surface of the mirror. To prevent these electrons from being detected, the cone of the channeltron was maintained at a bias of -300 V. The high voltage channeltron wires were shielded with earthed copper braiding and the voltage applied to the channeltron base was maintained at about 3.1 kV. This was typically 300-400V above the threshold voltage for detection. Some of the data runs were taken with a LiF window placed between the two chambers. This limited detection to features above approximately 105 nm (see Fig. 7). This greatly simplified the discussion of the He⁺, Ar, Kr, and Xe data (see later).

IV. 4 DATA COLLECTION

The schematic representation of the counting system can be found in Fig. 8. The pulses from the channeltron passed through the preamplifier, delay line amplifier, (Ortec 460) and integral discriminator, (Ortec 421) before arriving at the MCA, (The Nucleus Quantum 8 Multichannel Pulse Height Analyzer). At a given polarizer angle, the MCA sent a pulse
Figure 7: A plot of the transmittance of the LiF window as a function of wavelength.
Figure 8: A schematic representation of the counting system.
Figure 8

Diagram showing connections between various components such as Rate Meter, Integral Discriminator, Amp, Pre-Amp, Polarization Detector, LED Sensor, Multi-Channel Scaler, IBM PC/XT, Stepper Motor Driver, Stepper Motor, Ramp, IBM System Inc. Model 9000 Microcomputer.
to the ramp generator, (Tracor Northern 1251), incrementing the impact energy of the electrons. The ramp generator’s 0-12 V range was amplified by a DC to DC proportional converter, (Del Electronics PMS1-11). The normal dwell time was 1000 ms per channel. The MCA then incremented the impact energy again and collected on the next channel. There were 256 channels per angle and, after the MCA had finished ramping, the impact energy was reset to the initial value. Subsequently, the computer, which monitored the MCA’s progress, sent a series of pulses to a stepper motor driver. The driver then directed the stepper motor, in 1.8° steps, to the next desired angle, as indicated by one of four L.E.D. sensors.

The monitoring and controlling program of the computer was written in the Basic computer language and was designed to include features for reliability and convenience. The stepper motor, when properly aligned, could be operated continuously for months without missing an angle. Also, multiple sweeps and delay-times could be included to aid collection.

To ensure that the polarizer was aligned with the electron beam, a special diagnostic program was written. With provisions, such as eliminating the ramping impact energy, and allowing the MCA channels to be externally
controlled, we could collect polarization information for a
given impact energy, at 1.8° intervals. When plotted, as in
Fig. 9, we could determine if minimum and maximum photon
intensities were located on the desired axis, and if not,
the angle of correction. This also allowed us to determine
any asymmetry in the collection pattern. Asymmetries were
probably caused by mechanical or optical misalignment.
Intensity measurements were taken at four angles, rather
than two, to average any of these misalignments. This
introduced a systematic error of less than 1% into the
polarization data.

IV. 5 DATA ANALYSIS

After collection of information in the memory quadrants
of the MCA, the data was transmitted to another
microcomputer, (IBM Systems 9000) for analysis. The data
could be displayed in many forms, and stored using custom
data manipulation programs, again written in the Basic
computer language.

In order to obtain very accurate polarization data it
was essential to determine any background contribution,
Figure 9: A polarization ellipse showing the intensity (arbitrary units) as a function of polarizer angle. This example represents the unnormalized polarization of Helium at 80. eV impact energy. (The curve is offered merely as a guide to the eye.)
Figure 9
either from the residual background gas in the chamber or from impurities in the gas inlet line. To do this the following procedure was adopted:

In the near threshold region data was accumulated both without (curve 1) and with (curve 2) gas entering through the nozzle. (See Fig. 10.) Curve (1) was fitted with a high order polynomial least-square curve. Curve (1) was then scaled upwards (assuming that the impurity content was similar for the two cases) until the scaled curve, (3), coincided with curve (2) below threshold. Subtraction of curve (3) from curve (2) then enabled us to obtain true measured intensities for light polarized parallel ($\parallel$) and perpendicular ($\perp$) to the electron beam. The near coincidence of curves (2) and (3) below threshold supported the assumption regarding the nature of the background.

The energy of the incident electrons was calibrated to account for the contact potential of the electron gun. This contact potential was the result of various factors such as use of materials of different work functions and also charging of the surfaces near the cathode region. The calibration of the energy range was done using the threshold excitation function of the gas. The onset energy was compared with the known spectroscopic value. The contact potential was found to be less than 1 V throughout the experiment and was periodically checked.
Figure 10: An example of background subtraction for fictional data. See section IV.5 for details.
Example of Background Scaling

(Using fictional information)

Figure 10

Intensity (Arbitrary Units)

Energy (Arbitrary Units)
Recall that the fractional polarization of the emitted light was defined as:

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

(1)

where \(I_{\parallel}, I_{\perp}\) are the intensities of light observed at right angles to the electron beam and polarized parallel and perpendicular to the quantization (electron beam) axis, respectively. To determine \(I_{\parallel}\) and \(I_{\perp}\), we must first determine the detection properties of the polarizer. We know that:

\[
R_{\perp} = \frac{a^2 + b^2 - 2a \cos \theta \cos \phi}{a^2 + b^2 + 2a \cos \theta \cos \phi}
\]  

(26a)

and

\[
R_{\parallel} = R_{\perp} \left[ \frac{a^2 + b^2 - 2a \sin \theta \tan \phi + \sin \phi \tan \phi \tan \phi}{a^2 + b^2 + 2a \sin \theta \tan \phi + \sin \phi \tan \phi \tan \phi} \right]
\]  

(26b)

where \(R_{\parallel}\) and \(R_{\perp}\) are the reflection coefficients of gold for photons whose electric vector is parallel and perpendicular to the plane of incidence respectively, and \(a\) and \(b\) are given by:

\[
2a^2 = \left[ (n^2 - k^2 - \sin^2 \theta)^2 + 4n^2 k^2 \right]^{1/2} + (n^2 - k^2 - \sin^2 \theta)
\]  

(27a)
\[ 2b^2 = \left[ \left( n^2 - k^2 - \sin^2 \theta \right) + 4n^2k^2 \right]^{1/2} - \left( n^2 - k^2 - \sin^2 \theta \right) \]  

(27b)

where \( n \) is the real part of the index of refraction and \( k \) is the extinction coefficient. Then:

\[ I_{\|}^n = D \left( I_{\|} R_{\|} + I_{\perp} R_{\perp} \right) \]  

(28a)

and

\[ I_{\perp}^n = D \left( I_{\perp} R_{\|} + I_{\perp} R_{\perp} \right) \]  

(28b)

where \( D \) is the detection efficiency of the channel-electron multiplier, (assumed to be independent of the polarization of the photons\(^\text{29}\)). After some algebraic manipulation we find that:

\[ I_{\perp} = \frac{I_{\|}^n R_{\|} - I_{\perp}^n R_{\perp}}{D \left( R_{\|}^2 - R_{\perp}^2 \right)} \]  

(29a)

and

\[ I_{\|} = \frac{I_{\perp}^n R_{\|} - I_{\perp}^n R_{\perp}}{D \left( R_{\|}^2 - R_{\perp}^2 \right)} \]  

(29b)

Now if we substitute eqs. (29a) and (29b) into eq. (1) and simplify, we get:

\[ P = \left( \frac{R_{\|} + R_{\perp}}{R_{\|} - R_{\perp}} \right) \left( \frac{I_{\|}^m - I_{\perp}^m}{I_{\perp}^m + I_{\|}^m} \right) = \frac{1}{\eta} \left( \frac{I_{\|}^m - I_{\perp}^m}{I_{\perp}^m + I_{\|}^m} \right) \]  

(30)
where \( \eta \) is the polarization efficiency of the gold mirror. Thus:

\[
\frac{1}{\eta} = \frac{R_{\|} + R_{\perp}}{R_{\|} - R_{\perp}}
\]  

(31)

Using the calibration method described below we are able to determine \( \eta \) for the observed wavelengths.

IV.6 CALIBRATION

Our polarization information was dependent on the accuracy of the reflection coefficients of gold and the cleanliness of the gold surface. To calibrate our system, by partially decoupling the data from this dependence, three additional gold mirrors were placed in the path of the incident photons (Fig. 5). In this configuration, the total reflectance of the polarizer was the product of the reflectances of the individual mirrors.

Let \( R_{\|} \) and \( R_{\perp} \) be the reflection coefficients of mirror 1. Similarly, define \( R_{\|}^{2}, R_{\|}^{3}, R_{\|}^{4}, R_{\perp}^{2}, R_{\perp}^{3}, R_{\perp}^{4} \) for mirrors 2, 3, and 4. Now define the effective reflection coefficients:

\[
R_{\|} = R_{\|}^{2} R_{\|}^{3} R_{\|}^{4}, \quad \text{(32a)}
\]
\[ R_1 = R_1^1 R_1^2 R_1^3 R_1^4 \] \hspace{1cm} (32b)

and \( \eta \) becomes:

\[ \eta = \frac{R_1 - R_1}{R_1 + R_1} \] \hspace{1cm} (33)

or

\[ \eta = \frac{\left(\frac{R_1}{R_1} - 1\right)}{\left(\frac{R_1}{R_1} + 1\right)} \] \hspace{1cm} (34)

Typically,

\[ \frac{R_1}{R_1} \approx 5 \] \hspace{1cm} (35)

therefore:

\[ \frac{R_1}{R_1} \approx 5^4 \] \hspace{1cm} (36)

and

\[ \eta = \frac{624}{625} \] \hspace{1cm} (37)

(In practice a detailed calculation of \( \eta \) was carried out for each principle wavelength observed.) Consequently, for this
configuration, \( n \) is close to unity and virtually independent of any small errors in the published reflection coefficients. (These coefficients were derived from the work of Lynch and Hunter.\textsuperscript{30}) Unfortunately, the reduced signal from the absorption by each mirror makes this configuration impractical for data collection over a wide range of electron energies. As a result, information was collected for at least two reference energies for each gas. Typically 30 and 80 eV impact energies were used. Polarization data from the single mirror device were then normalized at these calibration points.

IV. 7 VACUUM SYSTEM

To minimize background effects, a base pressure of less than \( 1 \times 10^{-7} \) torr was maintained. This was accomplished through the use of a turbo-molecular pump (Edwards High Vacuum ETP160/1000) on each chamber. These were backed by a rotary pump with a molecular sieve trap. The pressure was measured using an ion gauge, (Veeco Instruments RG-75B with RG-83 controller) mounted 8 cm from the interaction region and 15 cm above the mouth of one of the pumps. To minimize
out-gassing, Viton O-rings were used. During times of inactivity, the gas line was evacuated to near-base pressures, thus minimizing contamination of the lines. Typically, the pressure in the chamber rose to about 2x10⁻⁷ torr, when gas was admitted through the hypodermic needle. Occasional baking of the system removed some accumulated impurities and minimized the base pressure.

IV.8 SOURCES OF ERROR

The principal sources of uncertainty in the polarization information presented in this work are a result of systematic errors. In some cases, the statistical error in all but the near threshold energy region is such that it can be considered insignificant. (The largest statistical scatter appears in the polarization of the 106.7 nm argon resonance line, as this data was accumulated at very low count rates. This error, however, constituted less than 2% of the polarization in all but the near threshold energy region.) Much effort has been expended in reducing the systematic errors and an accurate upper limit concerning their influence on the polarization can be made.
The energy scale for data collection ranges of 500 eV is less than 2 eV in error. The uncertainty reflects two principal contributions. The voltage drift of the electronics was observed to be less than .3 V at 500 eV for all data collection periods. The changes were monitored, and appeared to be the result of environmental influences. Non-linearities in the impact energy ramp generator may constitute a .3 eV shift in the energy scale at 500 eV. The error in the energy scale near threshold region was proportionately less.

The sensitivity of the channel-electron multiplier, as a function of wavelength, (see Fig. 6), varied slightly with time. This affected the relative measured intensities of the observed spectral features. The variation was due to the accumulation of water and other contaminants on the exposed and internal surfaces of the detector. The effect was monitored and when conditions warranted, the apparatus was halted and the contaminants removed. (The gold mirrors were also sensitive to contamination, but a regular cleaning program was adopted in addition to the calibration techniques described above, thus minimizing the effect.) This effect introduced an uncertainty of less than .3% into the results.

To confirm the position of the zero axis of the
polarization, the polarization of N$_2$ was measured at electron impact energies above 50 eV, and found to be equal to zero within error (Fig. 33). These values have been measured previously by Huschilt et al.\textsuperscript{17} and also found to be zero. This corroborated the position of the abscissa on the polarization versus electron energy plots as well the energy, $E_p$, for the other targets.

Variations in the polarizations due to current or pressure fluctuations were negligible, due to the data collection procedure. The dwell time at each angle was limited to 256 seconds, thus averaging any change in the conditions. Also, as stated previously, mechanical misalignments induced an error of less than 1\% into the polarization data.

The accumulation of these, and other less significant uncertainties is reflected in the stated errors for the data presented. In all cases (except in the near threshold region where a more detailed study is suggested) the total uncertainty did not exceed 5\%.
V. RESULTS AND DISCUSSION

Polarization data for several gases have been collected, with the results appearing in the following figures and for convenience, they have been tabulated in appendix A. Some relevant energy level diagrams are included in appendix B. The results of each gas are discussed separately:

V.1 HELIUM

Figure 11 shows the low energy polarization data for this target. The polarization at threshold was found to be .783 ± .060. This value is consistent with the predicted value of unity, if we take into account an electron beam energy width of about 500 meV. The polarization decreases as the impact energy is increased, with a minimum reached at about 26 eV. The polarization then rises to a secondary maximum value of over .57 at about 40 eV. (See Fig. 12 which covers the complete energy range.) Normally, we would expect the curve to extrapolate smoothly to unity at threshold from higher energies, but clearly this is not the
Figure 11: A plot of near threshold polarization as a function of impact energy for the target He.
Figure 12: A plot of polarization as a function of impact energy for the target He.
case. Although we may expect resonances to reduce the polarization somewhat, especially near threshold, no resonances should occur between the ionization threshold at 24.6 eV, and 50 eV. Hence, some mechanism, for example the electron-electron correlation mechanism proposed by Heideman et. al.\textsuperscript{11}, by which angular momentum can be shared between the excited and scattered electrons, must be responsible for this effect. Above 50 eV, (Fig. 12) the polarization then decreases, passing through zero at 375-10 eV. Clearly, the polarization has not attained its asymptotic value at 500 eV.

Figure 13 compares our polarization data to those of other groups. All other experimental data are limited to discrete points, whereas our data are continuous over the energy range from threshold to 500 eV. We note the good agreement with the data of Mumma et.al.\textsuperscript{11} at 50 eV and above. At lower energies our values are significantly higher than those of Mumma et.al. or Heddle and Lucas\textsuperscript{15}. We note the good agreement with the data of Steph and Golden,\textsuperscript{14} except that their 100 eV data point seems high. At lower energies, their data are larger than ours due to the depolarizing influence of cascade in our results. If we assume that the cascade component of our observed radiation is unpolarized then it is possible to correct our measured
Figure 13: Comparison of our polarization data

(△) with that of:

(+ ) Steph and Golden⁴
(□ ) Mumma et al.¹¹
(◇ ) Heddle and Lucas¹⁵
data for this effect using the fractional cascade component obtained by Donaldson et al.\textsuperscript{32} and Westerveld et al.\textsuperscript{21} We can show that:

\[ P = \frac{3P_m(1+\beta)}{(3+\beta P_m)} \]  \quad (38)

where \( P_m \) is the measured polarization and \( \beta \) is the cascade component of the total detected intensity. Figure 14 shows our low energy helium data corrected in this way and compared with the Steph and Golden results. These are seen to lie between our two curves.

Figure 15 shows the comparison between the current information and theoretical calculations. Perhaps surprisingly, the best agreement, above 50 eV, is given by the Born approximation.

The measured slope \( \mathcal{C} \), (eq. 25a) evaluated at \( P=0 \) was found to be \( -0.224\pm0.005 \). Assuming a value of \( \beta=0.05 \), which is consistent with the findings of Donaldson et al.\textsuperscript{32} leads to a value of \( P_L \) of \( 0.96\pm0.15 \). This may be compared with the expected value of unity.

Values of \( \mathcal{C} \), (see eq. 22) have been calculated and are listed by Donaldson et al.\textsuperscript{32} These range from \( 0.124 \) for the \( 2^1P \) state to \( 0.159 \) for the \( 4^1P \) state. Using the observed value of \( E \), for the integrated radiation we deduce

65
Figure 14: Low energy Helium polarization uncorrected (—) and corrected (---) for cascade and compared with the results of Steph and Golden\textsuperscript{14} (0)
Figure 14

[Image of a graph showing a plot of electron energy (eV) against an axis labeled 'P'. The graph includes data points and error bars.]
Figure 15: A plot of our polarization of helium (---) compared with that of:
(---) First Order Many Body Theory
(-- -) Born approximation
(-----) Glauber approximation
a $c$, value of 0.182. This is rather larger than any of the calculated values. This tendency for the Bethe approximation to over estimate the value of $E$, has also been noted in the case of $L$, excitation in hydrogen.\textsuperscript{26}

V.2 HELIUM II

The polarization of the observable wavelengths of helium II can be found in Figs. 16 and 17. The polarization at threshold was found to be .200±.050, and decreases from this value to a plateau feature that extends from 90 to 110 eV. It then decreases, but does not cross the zero axis below 500 eV.

The threshold polarization offers the possibility of extracting the relative contributions of the three contributing sublevels (see Table 2). This method was first proposed by McConkey.\textsuperscript{8} The polarization of the $2p - 4s$ transition must be zero, as the $s$ state is spherically symmetric. The threshold polarization for the $2p - 4d$ and $2s - 4p$ transitions can be calculated using eq. (16). These
Figure 16: A plot of near threshold polarization as a function of impact energy for the target He II.
Figure 17: A plot of the polarization as a function of impact energy for the target He II. (The dashed line represents extrapolation to threshold. See text.)
are .490 and .425 respectively. It can be shown that:

\[ I_{\|} = \left( \frac{1+P}{3-P} \right) I \]  

(39)

and

\[ I_\perp = \left( \frac{1-P}{3-P} \right) I \]  

(40)

also,

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

(41)

therefore:

\[ P_{i} = \frac{[.330 I(2s-4p) + .391 I(2p-4d)]}{[.667 I(2p-4s) + .776 I(2s-4p) + .797 I(2p-4d)]} \]  

(42)

where \( I(2p-4s) \), \( I(2s-4p) \), and \( I(2p-4d) \) are the total intensities of the appropriate transition. Let

\[ I = QB \]  

(43)

where \( Q \) is the total cross section and \( B \) is the branching ratio for the observed transition. If we assume the theoretical hydrogenic branching ratios,\(^{33}\) for the above transitions, namely \( B(4s-2p) = .58 \), \( B(4p-2s) = .12 \), and \( B(4d-2p) = .75 \) and that:
\[ Q(4p) \approx Q(4d) \] (44)

as was obtained at energies above 200 eV.\textsuperscript{34} Equation (41) can be changed to the form:

\[
\frac{Q(4s)}{Q(4d+4p)} = \frac{0.33-P_1(0.692)}{P_1(0.386)}
\] (45)

Using our measured value of \( P_1 = 0.2 \) we get:

\[
\frac{Q(4s)}{Q(4d+4p)} \approx 2.5
\] (46)

Thus if we neglect the effect of resonances and electron correlation effects, the threshold polarization and excitation functions are dominated by the 4s - 2p transition. We note that the theoretical calculations\textsuperscript{34} carried out for much higher impact energies (\( \geq 200 \) eV) also reveal a dominance of \( Q(4s) \) over \( Q(4p) \) and \( Q(4d) \).

If we assume that the drop in the polarization at threshold is due to some effect other than the relative cross sections of the 4s, 4p, and 4d states, then we can project the polarization back to threshold (Fig. 17), and obtain \( P_1 = 0.180 \). Equation (45) then yields:

\[
\frac{Q(4s)}{Q(4d+4p)} = 2.96
\] (47)
This also suggests that the cross section of the 4s state is dominant at threshold. Although the apparatus used in this work was not designed to extract apparent cross sections, we can still make some comparisons to existing work. We can take the measured intensities, $I^n_m$ and $I^n_l$, and extract from them the relative cross section information as discussed below.

To determine the relative cross section of He II, we begin with eq. (43):

$$I \propto QB$$  \hspace{1cm} (43)

and

$$I = I^n_d + 2I^n_s$$  \hspace{1cm} (48)

from eqs. (29a) and (29b) we get:

$$I = \frac{I^n_d (R^n_d - 2R^n_s) + I^n_s (2R^n_d - R^n_s)}{R^n_d^2 - R^n_s^2}$$  \hspace{1cm} (49)

We know that for the observed lines of He II:\(^{30}\)

$$R^n_s = .073, \quad R^n_d = .400$$  \hspace{1cm} (50a,b)

Therefore,

$$I = 1.63I^n_d + 4.70I^n_s$$  \hspace{1cm} (51)

or
If we insert our observed excitation functions into eq. (52), we can determine the shape of the apparent cross section. The results, normalized at 500 eV and compared to the results of Forand et. al., appear in Fig. 18. We note the good agreement especially if one considers the uncertainties involved. If we then display this same information, expressed as $Q\epsilon$, vs. $E$, (Fig. 19) we note that $Q\epsilon$ is approaching a constant value as the energy is increased. This is what would be expected for an optically forbidden excitation process. Since simultaneous ionization and excitation is a two electron process it clearly falls into this category.

V.3 NEON

The interpretation of the data acquired from neon is difficult, due to the abundance of cascade contributions to the resonance lines, and the fact that the detector is sensitive to other spectral components of the gas. The principal observed spectral contributions come from the
Figure 18: The excitation function of He II normalized to the results of Forand et al. \textsuperscript{35} at 500 eV. + represents the results of Forand et al.
Figure 19: A plot of $Q_f$ versus electron energy for He II. $Q$ is proportional to the cross section and $E$ is the electron impact energy. The results are normalized to, and compared with the work of Forand et al. [35]
resonance lines of the neutral atom at 73.6 and 74.4 nm and from the ion at 46.1 and 46.2 nm.

At threshold, (Fig. 20) there is little indication of the high polarization that is predicted by angular momentum arguments. It seems reasonable that this may be due to the strength of the resonances which occur in this region. The polarization is seen to rise to a peak value near 40 eV, and decrease (Fig. 21) to cross the zero axis at 327±10 eV.

To our knowledge, there has been no polarization information presented regarding neon, but some comparisons to other information can be made. The cascade contribution is considered to be unpolarized as are the Ne⁺ resonance lines. We then must have strongly polarized neutral resonance lines, but a reduced polarization because of these unpolarized sources. We can collect the contributions of these unpolarized sources into one effective β from eq. (25a). Phillips et al. have measured the apparent cross section of the two neutral resonance lines and found them to be 7.8×10⁻¹⁸ cm² at 300 eV with a cascade contribution of 29%. If we use van Raan's cross section values and take into account the detection efficiency of our apparatus, we calculate a cross section value for the Ne⁺ 46 nm lines, of 3.9×10⁻¹⁸ cm², also at 300 eV. Thus we obtain an effective β of 1.1 and hence P⁺ from eq. (25a) is 0.84. This value
Figure 20: A plot of the near threshold polarization as a function of impact energy for the target Ne.
Figure 20.
Figure 21: Polarization plotted as a function of the impact energy for the target Ne.
is in agreement with the expected value of unity, given the large uncertainties involved. Alternatively, we might assume $P$, to be unity and calculate an effective $\beta$ of 1.69.

van Raan\textsuperscript{39} has measured the parameter $c_{11}$ in eq. (22), for the 736 nm transition. He finds $c = .175$, which leads to a value of $E_c = 390$ eV. This is higher than our measured value of 327 eV. The difference is probably due to the sensitivity of our detector to the additional spectral features discussed earlier.

V.4 ARGON

The polarization of argon, (Fig. 22) is more difficult to analyze than neon because of the abundance of spectral features which are observed (Table 2). (See also McConkey and Donaldson.\textsuperscript{40}) There is some indication of a peak at threshold but the presence of strong negative ion resonances\textsuperscript{36} seems to decrease the polarization to a minimum at about 16 eV (Fig. 23). The polarization then rises to a peak at about 35 eV and drops to a "shoulder" feature at about 60 eV. It then steadily decreases and crosses
Figure 22: A plot of the polarization of Ar measured with (x) and without (+) the LiF window in place.
<table>
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<th>Wavelength</th>
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<th>Wavelength</th>
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<td>1396.231Å</td>
<td>3d-7f</td>
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Figure 23: A plot of the near threshold polarization of argon measured with (x) and without (+) the LiF window in place.
zero at 307:10 eV, with a slope of \( C_1 \) of \(-1.16 \pm 0.05\).

The low polarization below 30 eV may be due, in part, to a large cascade contribution to the argon resonance lines as well as a low or negative polarization of the 106.7 nm line. (This will be discussed in more detail below.) The "shoulder" feature is associated with the second peak in the excitation function which occurred at this energy. The many spectral components have been examined by McConkey and Donaldson\(^4\) at 100 eV and Ajello et al.\(^3\) at 200 eV. Both spectra indicate strong ArI and ArII constituents (Table 2). Below 29.2 eV, the threshold for ArII radiation, only ArI lines are detected. The major contributions to the excitation function and thus the polarization in this energy region are made by the 104.8 nm and the 106.7 nm neutral resonance lines. The situation can be simplified if principally the 106.7 nm line is observed. This was accomplished by using a LiF window in front of the polarization analyzer. The window absorbs most of the radiation below 105.0 nm (Fig. 7), thus allowing us to determine the polarization of the radiation from the so-called "singlet" and the "triplet" state as discussed below. (These states designations arise because of the mixed singlet/triplet nature of these states.)

Figure 24 compares excitation functions taken with and without the LiF window. We note the large extra contributions above 30 eV observed with no window. This has a
Figure 24: The excitation function of argon measured with (+) (x10) and without (x) the LiF window.
double humped structure typical of argon II excitation\textsuperscript{41} and an onset which is consistent with this identification. The much smaller structures on the lower curve are probably the result of residual argon II lines (Table 2) being transmitted through the LiF window. The first peak in the excitation function data at 24 eV may be identified with neutral argon excitation, principally the 104.8 and 106.7 nm lines, as it is seen primarily with the LiF filtered data.

Figure 23, which shows the near threshold polarizations, indicates a lower overall polarization with the LiF filtered data. Since use of the window will enhance the 106.7 nm line over the 104.6 nm line, this strongly suggests that the polarization of the former line is significantly lower. If we assume that in this low energy region the polarization data are dominated by these two lines, then we can estimate the individual polarization using the following analysis.

The polarization, \( P \), of the 104.8 nm line is:

\[
P = \frac{1/II - 1/I_l}{1/II + 1/I_l}
\]  

(53a)

where \(^1\)I indicates the characteristics of the radiation from the "singlet state". The polarization of the 106.7 nm line is given by:
\[ 3P = \frac{3I_{11} - 3I_1}{3I_{11} + 3I_1} \]  

(53b)

where \(^3I\) indicates the characteristics of the radiation from the "triplet" state. The measured polarization of both states can be shown to be:

\[ \mathcal{M}P = \frac{1P\left[ \frac{1}{I_{11}} + \frac{1}{I_1} \right] + 3P\left[ \frac{3}{I_{11}} + \frac{3}{I_1} \right]}{\left[ \frac{1}{I_{11}} + \frac{1}{I_1} \right] + \left[ \frac{3}{I_{11}} + \frac{3}{I_1} \right]} \]  

(54a)

Now if we consider the effects of the LiF window, we find that:

\[ P' = \alpha\left[ \frac{1}{I_{11}} - \frac{1}{I_1} \right] + \beta\left[ \frac{3}{I_{11}} - \frac{3}{I_1} \right] \]  

\[ \frac{\alpha}{\alpha + \beta} \]  

(54b)

where \(\alpha\) is the absorption coefficient of the LiF window for the 104.8 nm line and \(\beta\) is the absorption coefficient of the window for the 106.7 nm line. We can show that:

\[ 3P = \frac{(1 + fR)P' - (1 + R)P}{R(f - 1)} \]  

(55a)

and

\[ \nu P = \frac{(1 + R)fP' - (1 + fR)P'}{f - 1} \]  

(55b)

where
\[ R = \left( \frac{\frac{\frac{3}{2}I_{||} + \frac{1}{2}I_{\perp}}{I_{||}} + \frac{1}{2}I_{\perp}}{I_{||} + 2I_{\perp}} \right) \]  \hspace{1cm} (56)

and

\[ f = \frac{B}{A} \]  \hspace{1cm} (57)

Donaldson et. al.\(^{32}\) have measured the ratio:

\[ R' = \left( \frac{\frac{3}{2}I_{||} + \frac{1}{2}I_{\perp}}{I_{||} + 2I_{\perp}} \right) = \frac{3}{2} \]  \hspace{1cm} (58)

we can relate \( R \) and \( R' \) by using

\[ I_{||} + I_{\perp} = \frac{2I}{3 - P} \]  \hspace{1cm} (59)

Thus,

\[ R = R' \left[ \frac{3 - 3P}{3 - 3P} \right] \]  \hspace{1cm} (60)

we can solve eqs. (56a),(56b), and (60) by means of iteration, and thus get the individual polarizations of the 104.8 and 106.7 nm lines assuming \( f \) is known. In actual fact the results were found to be rather insensitive to the values chosen for \( f \). The data shown in Table 3 were calculated assuming \( f = 5 \). (It is planned to measure \( f \) in a
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Table 3: Argon 1P and 3P Polarizations
future experiment, at which time any necessary modifications can be made to the data in Table 3. The most significant input from Table 3 is the very high, essentially unity, polarization of the "singlet" line at threshold, coupled with the small negative polarization for the "triplet".

In addition to the polarization of the unfiltered radiation, Fig. 22 shows the polarization of the radiation, as seen through the LiF window. The polarization of the filtered radiation crosses the zero axis at $218\pm15$ eV, with a slope, $C'$, of $-0.10\pm0.01$. This crossover energy value is 89 eV lower than that of the unfiltered radiation. If we use eq. (25a) and assume a threshold of unity, we can calculate an effective unpolarized cascade component $\beta$, of .237 at 218 eV.

Using the $c=0.38\pm0.10$, as determined by McConkey and Donaldson, we then calculate the energy of the zero polarization crossover as 180.64 eV. Clearly the higher measured value is largely due to the influence of the argon II line observed with our apparatus.
The polarization of krypton (Figs. 25 and 26) rises from a threshold value near zero to a peak near 30 eV. It then decreases steadily to zero at 272±10 eV. The polarization is interesting in its contrast with the polarization measured with the LiF filter in place. The spectral components detected through the filter (Table 2) are a result of the excitation of a 4p outer shell electron into a 5s orbital, with a subsequent decay back to the $^1S_0$ ground state. In the energy region between threshold and 27 eV these 2 curves virtually coincide. This supports the supposition that the excitation and polarization functions are dominated by the 4p-5s transitions in this region.

Above 27 eV the excitation function is influenced by contributions from the KrII lines. (These have an effective threshold of 26.8 eV.) Since these lines have a wavelength of less than 100 nm, they do not affect the polarization of the filtered radiation, and we see a divergence of the 2 curves. The polarization of the 4p-5s transitions is peaked at about 32 eV and decreases to cross the abscissa at 212±10 eV (Fig. 27). Using eq. (25a), (neglecting the effects of cascade) the slope at the crossover point, $-1.33\times0.05$, corresponds to a threshold polarization of $0.63\times0.02$. If we
Figure 25: A plot of near threshold polarization of krypton measured with (+) and without (x) the LiF window in place.
Figure 26: The polarization of krypton plotted as a function of impact energy.
Figure 27: A plot of the polarization of krypton measured with the LiF window in place.
assume the divergence of this from unity is due to cascade then we can estimate the fractional cascade component, \( \beta \), to be .88.

The fact that the measured threshold polarization is indistinguishable from zero supports the idea that resonances play an important role in near threshold excitation.

V.6 XENON

As with the other heavy gases, the interpretation of the polarization of xenon is complicated by the large number of spectral components that are detected. Unlike most other gases, however, the situation is not drastically simplified by the addition of a LiF window to the path of the photons. This is because many of the Xenon I and Xenon II lines have wavelengths longer than the 105.0 nm cutoff (see Table 2). As a result, the polarizations with and without the filter virtually coincide between threshold and about 30 eV (Fig. 28). The polarization shows a peak at threshold, but quickly decreases to a minimum at about 11eV. This is probably due to negative ion resonances once again. It then rises to a second peak at about 23 eV and drops to a second minimum at about 30 eV. This feature corresponds to the
Figure 28: A plot of near threshold polarization of xenon measured with (+) and without (x) the LiF window in place.
Figure 29: A plot of the excitation functions of xenon measured with (+) and without (x) the LiF window.
influence of the XeII lines which have an onset at 23.4 eV and appear to be initially unpolarized. (Fig. 29 shows a comparison between the excitation functions measured with and without the LiF filter.) The polarization then rises again to a peak near 50 eV, and decreases to cross the axis at 210.10 eV (Fig. 30). The slope at the crossover, $C'$, is $-0.091 \pm 0.005$, and neglecting cascade, leads to $P_e$ of 0.46. If we assume $P_e = 1$ then we can deduce an effective cascade fraction of 1.75. The polarization does not reach any asymptotic value by 500 eV.

V. 7 HYDROGEN AND NITROGEN

The polarization of hydrogen and nitrogen appear in Figs. (31), (32), and (33). For background information on the polarization of molecular radiation the reader is referred to the work of Dassen and McConkey\textsuperscript{42} and Huschilt et al.\textsuperscript{17} No attempt is made here to analyze the data because of the large number of spectral features due to both direct and dissociative excitation which can affect our detector.
Figure 30: A plot of polarization of xenon measured with (x) and without (+) the LiF window.
Figure 30
Figure 31: A plot of near threshold polarization of H₂ as a function of impact energy.
Figure 32: Polarization of $H_2$ as a function of impact energy.
Figure 32

Electron Energy (eV)

P

0.15  0.1  0.05  0  -0.05  -0.1

0  200  400
Figure 33: A plot of the polarization of $N_2$ as a function of impact energy.
VI. CONCLUSION AND SUGGESTIONS

The polarization of V.U.V. atomic line radiation following electron impact has been experimentally investigated for the targets He, He⁺, Ne, Ar, Kr, Xe, H₂, and N₂ over an impact energy range from threshold to 500 eV. A crossed electron-gas beam system has been used in conjunction with a single reflection, gold surfaced, polarization analyzer. Threshold polarizations have been compared with values deduced from angular momentum arguments, and particular attention has been paid to the energy region where the polarization changes sign. From the data collected it was possible to make the following conclusions:

a) Measured threshold polarizations in helium were found to be consistent with predictions based on angular momentum arguments given the energy spread of the electron beam. For the other targets, threshold polarizations values calculated from the slopes of the polarization curves, as they pass thought zero, making use of the Born approximation, agree with values
predicted from angular momentum considerations provided cascade is properly accounted for.

b) Resonances are shown to exert a strong perturbing effect on polarization functions. This effect is responsible for drastically reduced polarizations near threshold.

c) Some other effect, possibly the electron correlation phenomenon proposed by Heideman et. al.,\(^{31}\) is responsible for reducing the polarization in energy regions beyond the influence of resonances.

The information presented in this work has been limited to an impact energy of 0 - 500 eV, with an energy resolution of about 500 meV. In order to determine more meaningful threshold polarizations, work needs to be done using an energy selected electron beam. Since resonances may exert large effects on the polarization, and relatively small effects on the excitation cross section, an energy selected electron beam can also be used to probe these resonance structures. In addition, angular momentum arguments suggest an asymptotic value for the polarization at high electron energy (>500 eV). This phenomenon has, to our knowledge,
not been investigated, and warrants further attention.
## Appendix A: Polarizations of Various Gases

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Appendix B: Energy Level Diagram for He
Appendix B: Energy Level Diagram for Ar

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\[ \text{Ar } (1s^2 2s^2 2p^6 3s^2 3p^6) \]

\[ 3p^6 S_0 \]
Appendix B: Energy Level Diagram for Ar II

![Energy Level Diagram for Ar II](image-url)
REFERENCES

1. Investigations included many of the references listed below. Some early references include:
   - K. Steiner, Z. Phys. 52, 516 (1929);
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