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ABSOLUTE EXPERIMENTAL CROSS SECTIONS FOR THE EXCITATION
OF BARIUM IONS BY ELECTRON IMPACT

A THESIS

Presented to

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by

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OF BARIUM IONS BY ELECTRON IMPACT

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SUMMARY

The crossed beam technique has been used to measure absolute emission cross sections for the excitation of electric dipole transitions in the Ba^+ ion by electron impact at energies near and below threshold. The basic experimental method involves intersecting modulated ion and electron beams at right angles in a well defined collision volume. A portion of the photon flux radiated from the collision volume by excited ions is detected by an optical system viewing the collision volume along the axis perpendicular to both beams. The total emission is calculated from the portion detected using the experimentally determined response of the detection system to isotropic radiation and a correction for anisotropy, obtained from the polarization of detected emission. The emission cross section is then calculated from the total emission, the two beam currents and their spatial distributions, and the energies.

The cross sections measured are absolute in the strict sense that the optical detection system was calibrated with a light standard by a technique which takes into account all spatial and spectral variations. A stable point source of light has been devised to determine the variation of the detection system response with the position in the collision volume where the photons are produced. Another small light source has been developed for transferring to the detection system the calibration of a tungsten ribbon standard of spectral radiance traceable to black-body standards. Techniques of careful spectral comparison of the sources

are used for this purpose.

An electron source has been developed with the energy resolution and current necessary for crossed beam measurements in the 3-20 eV range. This tool made possible the examination of the range of impact energies near and below the excitation threshold.

The only other experimental result available for comparison is in agreement well within the combined experimental uncertainty. Available theoretical calculations compare poorly with the present results, as well as with each other. This is attributed to the rather drastic approximations used in the theoretical calculations. The results obtained from the Born approximation apparently overestimate the cross section, which is typical for that type of calculation at low energies.

CHAPTER I

INTRODUCTION

Absolute emission cross sections^{*} have been measured for electron impact excitation of the resonance transitions in the Ba^+ ion. The process of exciting emission by electron impact can be described by the following two equations:

As seen in the energy level diagram¹ in Figure 1, the resonance transitions occur between the $6^2\text{P}_{1/2}^0$ and $6^2\text{P}_{3/2}^0$ levels and the $6^2\text{S}_{1/2}$ ground state with emission of photons with wavelengths 4934 Å and 4554 Å, respectively. The threshold energies for exciting the $6^2\text{P}_{1/2}^0$ and $6^2\text{P}_{3/2}^0$ levels from the $6^2\text{S}_{1/2}$ ground state are 2.5 eV and 2.7 eV, respectively.

The experimental method involves crossing modulated beams of ions and electrons in a well defined collision volume. An ion excited by an electron collision emits a photon in an electric dipole transition before moving a millimeter, because the excited state lifetimes are approximately 10^{-8} seconds and the ion velocity is approximately 10^7 millimeters per second. A portion of the radiation from excited ions is detected by

^{*}The absolute emission cross section is defined in Appendix I.

Figure 1. Energy Level Diagram of Ba^+ .

direct observation of the collision volume with a photomultiplier tube operated in the counting mode. A single resonance line is selected with a narrow band interference filter. The cross section for emission of photons of the selected wavelength is obtained from the observed photon flux and other experimental parameters. A new electron source has been developed for this experiment which produces sufficient current with a narrow beam energy spread. This tool has made possible the examination of the range of impact energies near and below the excitation threshold. The cross sections are made absolute, in the sense that the optical measurements are related to a light standard, with techniques developed in this experiment to absolutely calibrate a photon detection system operated in the counting mode. The entire experimental technique is presented in Chapter II.

The first crossed beam study of ion excitation by electron impact was the experiment of Dance, Harrison, and Smith² involving the 2S level of He^+ . It should be noted that there is a basic difference between their experiment and this one, which requires direct observation of the collision volume. The 2S state excited in the experiment of Dance, et al. is metastable, and they detected ions in this state with an electric quench field located downstream from the collision volume, where there was less noise from spontaneous transitions and hot surfaces in the sources. This quench field effected Stark mixing of the metastable 2S state and the 2P state, and the spontaneous photon emission from the latter state was detected. Their technique appears possible only for hydrogenic structures having ordinary excited states very close to the

metastable state so that an applied electric field can produce considerable overlap of the wavefunction of the metastable state with that of a state from which spontaneous emission occurs.

In a crossed beam study of the excitation of Ba^+ ions by electron impact, Bacon³ observed spontaneous photon emission from the excited ions in the collision volume. He established the basic techniques for measuring emission cross sections by direct observation of the collision volume. Bacon's cross sections were relative in the sense that the absolute scale of the cross section as a function of impact energy was undetermined.

The crossed beam technique has also been applied to ion excitation by electron impact by Lee and Carleton,⁴ who have reported emission cross sections for excitation of N_2^+ ions. The lowest impact energy considered in their experiment was 5 eV, while the threshold energy for excitation was 3.1 eV. The excitation state of the N_2^+ beam, which was produced in an electron bombardment discharge source, could not be completely ascertained. Only the electron beam was modulated. Resolution of variation in the cross section with energy was impaired by the electron beam energy spread of approximately 2 eV.

A practical incentive for measuring absolute emission cross sections for the Ba^+ resonance lines for electron impact energies near the excitation threshold is found in the controlled thermonuclear program. Barium is used in experimental plasmas because it can be ionized on hot surfaces and because optical diagnosis of the plasma through observation of the resonance lines is convenient. Ion and electron temperatures and densities can be studied by observation of the self-excited resonance

radiation emitted from the plasma.⁵⁻¹⁶ Since the self-excitation occurs by electron impact with impact energies near the excitation threshold, the present experimental results are of direct practical interest.

The present experimental results are also of interest for comparison with available theoretical calculations. The conventional theoretical approach is to expand the wavefunction for the entire system of ion and interacting electron in terms of the unperturbed wavefunctions of the ion and electron. The time independent Schrodinger equation to be solved for the wavefunction of the entire system contains the ion-electron interaction as a perturbation added to the Hamiltonian. The problem is one of solving an infinite set of coupled differential equations through resort to some approximation in which only a selected few of these equations must be solved.

The Born approximation reduces the infinite set of differential equations to only one by assuming the projectile electron is unaffected in the collision and that the only effect on the ion is the coupling of that pair of ion eigenstates involved in the excitation. The Bethe-Born approximation is the same as the Born, except that it makes mathematical approximations to the final result of the Born approximation. The Coulomb-Born approximation proceeds as the Born approximation, but the former assumes wavefunctions for the projectile electron that represent a charged particle in a Coulomb field, while plane waves are used for the electron in the ordinary Born approximation. Calculations using the Coulomb-Born approximation have been applied to electron impact excitation of hydrogenic ions by Tully,¹⁷ Burgess,¹⁸ and Gailitis.¹⁹ Excitation of the barium ion has been treated with the Coulomb-Born approximation by

Petrini.²⁰ The Bethe-Born result for excitation of neutrals has been applied to the case of ion excitation by electrons through the use of an empirical factor by Seaton.²¹

The close-coupling calculation is more elaborate than the Born approximation. While the Born approximation circumvents the problem of solving an infinite set of coupled differential equations by neglecting all but one, the close-coupling calculation treats selected coupled equations by retaining the terms involving several of the lowest lying eigenstates of the ion. No close-coupling calculations have been applied to the barium ion, but the close-coupling calculations of Burke and Moores²² on the excitation of Ca^+ and Mg^+ have been found to agree well with Coulomb-Born calculations. Coulomb-Born approximations applied to the excitation of Ba^+ by electron impact are compared with the present experimental results in Chapter V.

CHAPTER II

EXPERIMENTAL TECHNIQUE

The experimental procedures may be divided into two basic categories: absolute calibration of the optical detection system, and measurement of cross sections with the crossed beam apparatus. In this chapter the experimental techniques used in calibration and cross section measurements are discussed in reference to expressions giving the cross sections in terms of experimental parameters.

The basic experimental method is to perpendicularly intersect monoenergetic beams of Ba^+ ions and electrons in a well defined collision volume, as shown in Figure 2. Ba^+ ions excited by electron impact emit photons in electric dipole transitions before moving a fraction of a millimeter from the point of excitation. A lens system collects a fraction of the photon flux that is radiated from the collision volume in a direction perpendicular to both beams and directs it through a window in the vacuum chamber. A narrow band interference filter selects one of the resonance lines, and the photon flux at that wavelength is measured by a photomultiplier operated in the counting mode.

The absolute emission cross sections are calculated from the experimental data by means of the following equations:

$$\sigma_{4554} = \frac{S(1-\frac{1}{3}P)}{D_{4554}} \frac{e^2 V_i V_e}{\sqrt{V_i^2 + V_e^2}} \frac{F}{I_i I_e} \quad (3)$$

Figure 2. Schematic of Photon Production and Collection

$$\sigma_{4934} = \frac{S(1-\frac{1}{3}P)}{D_{4934}} \frac{e^2 V_i V_e}{\sqrt{V_i^2 + V_e^2}} \frac{F}{I_i I_e} \quad (4)$$

$$F = \frac{\int J_i(z) dz \quad \int J_e(z) dz}{\int J_i(z) J_e(z) dz} \quad (5)$$

where S is the count rate observed due to the photons of interest, D_{4554} and D_{4934} are the photon detection efficiencies of the detection system at the two resonance wavelengths, e is the electronic charge, I_i and I_e are the total currents of ions and electrons, V_i and V_e are the velocities of ions and electrons, $J_i(z)dz$ and $J_e(z)dz$ are ion and electron currents between z and $z+dz$, and P represents the polarization of the photons collected. The role of each of these experimental parameters in the cross section formulas is identified in Table 1. The derivation of the cross section formulas is presented in Appendix I. The experimental techniques for determining the parameters in Table 1 are discussed in this chapter.

Determination of Total Photon Emission

In this experiment allowance must be made for the fact that only a fraction of the total photon emission is registered as counts in the detection system. This fraction depends on both the angular distribution of photon flux radiated from the collision volume and the fraction of photons radiated toward the detection system that are actually registered as counts. The effect of the angular distribution of photon flux is included

Table 1. Association of Salient Features of the Experiment
with Parameters in Cross Section Formulas

Parameter	Associated Feature of Experiment
$\frac{D_{4554}}{D_{4934}}$	photon detection efficiency of detector
$\frac{eV_i}{I_i}$	density of ions
$\frac{eV_e}{I_e}$	density of electrons
F	extent to which the beams overlap
$\sqrt{V_i^2 + V_e^2}$	relative velocity of ions and electrons
σ	effective size of fictitious target with which the projectile electron must interact in the classical sense to cause emission of a photon from a Ba^+ ion
$(1 - \frac{1}{3}P)$	anisotropy of radiation from collision volume

in the factor $(1 - \frac{1}{3}P)$, which represents the ratio of the actual anisotropic flux radiated toward the detector to an equivalent isotropic photon flux that is equivalent in that it represents the actual total photon emission. The optical detection efficiencies D_{4554} and D_{4934} represent the fraction of the photons with the resonance line wavelengths in an isotropic flux emanating from the collision volume that will actually be registered as counts by the detection system. Therefore, the combination $\frac{S(1 - \frac{1}{3}P)}{D}$ represents the total photon emission. The experimental determinations of the parameters S , P , D_{4934} , and D_{4554} are discussed in later sections of this chapter.

Correction for Anisotropy by Measurement of Polarization

The angular distribution of photon flux radiated from the collision volume is revealed by the polarization of those photons radiated toward the detector. The theory of quantum electrodynamics shows that dipole radiation from an ion excited by electron impact may be regarded as the radiation from three mutually perpendicular dipoles, one along the axis of each beam and the third perpendicular to both beam axes. The strengths of the two dipoles oriented respectively along the ion beam and perpendicular to both beams are equal by symmetry, but the strength of the dipole along the electron beam axis is generally different from the other two. That is because the motion of the exciting electrons introduces a preferred axis. The angular distribution of radiation from this combination of dipoles is then calculated in a straightforward manner from the radiation pattern of a single dipole, provided the relative strengths of the three dipoles are known.

The relative strengths of the three perpendicular dipoles representing the radiating ions are experimentally determined by observing the polarization of the photons radiated in the direction of the detector. The relative strengths of the dipoles along the two beam axes are established through knowledge of the polarization of the photons radiated toward the detector, since the photons radiated by a dipole in a direction perpendicular to that dipole are polarized with electric vectors along the dipole direction. The third dipole representing the radiating ions is pointed toward the detector, and it therefore does not radiate to the detector; however, from the symmetry about the electron beam the strength of this dipole is known to be the same as the strength of the dipole along the ion beam axis.

The angular distribution of photon flux radiated from the collision volume has been computed by Percival and Seaton²³ in terms of the polarization of the photons radiated to the detector. A polarization fraction is defined by

$$P = \frac{\Phi_{\parallel} - \Phi_{\perp}}{\Phi_{\parallel} + \Phi_{\perp}} \quad (6)$$

where $\Phi_{\parallel}$ and $\Phi_{\perp}$ are the photon fluxes radiated toward the detector with electric vectors polarized respectively parallel and perpendicular to the electron beam. Percival and Seaton show that the average flux over all solid angles is $(1 - \frac{1}{3}P)$ times the flux radiated toward the detector. Therefore, multiplication by $(1 - \frac{1}{3}P)$ converts the photon flux received by the detector to an equivalent isotropic photon flux representing the same photon emission.

The polarization fraction P is experimentally determined by counting photons of the desired wavelength with a linear polarizer in the optical path. The polarizer axis is oriented along the electron beam to determine $\Phi_{\parallel}$, and the axis is oriented perpendicular to the electron beam to determine $\Phi_{\perp}$. The incomplete transmission by the polarizer of photons having the selected polarization affects the values of $\Phi_{\parallel}$ and $\Phi_{\perp}$ by the same factor, and the fraction P is thus unaffected.

Absolute Optical Calibration of the Photon Detection System

Absolute calibration of the photon detection system requires the determination of that function of space and wavelength which specifies, for each wavelength of interest and each point in the collision volume, the fraction of the photons produced there that is actually registered as counts in the detection system. Since the factor $(1 - \frac{1}{3}P)$ converts the actual photon flux detected to an equivalent isotropic photon flux, the absolute optical calibration is determined for isotropic photon radiation from the collision volume. This calibration takes into account all detection system characteristics such as optical collection efficiency, window transmissions, filter transmission, and photomultiplier quantum efficiency. The procedures involved in the experimental determination of the absolute optical calibration may be divided into three parts: (1) relative optical calibration, (2) calibration of a secondary standard of spectral radiance with a primary standard, and (3) transference of the absolute calibration to the detection system by means of the secondary standard of spectral radiance.

Relative Optical Calibration. In the relative optical calibration a determination is made of the spatial portion of the detection efficiency

function, i.e. the variation of photon detection efficiency with the position in the collision volume where the photons are produced.

The relative spatial variation of photon detection efficiency is determined by ascertaining the detection system response to a stable point source of light located at various known positions in the collision volume. Background noise counts in the detection system are eliminated by taking the system response with the source turned off. The relative spatial variation thus determined is designated by a function $n(x,y,z)$ with arbitrary amplitude.

Comparison of a Secondary Standard of Spectral Radiance with a Primary Standard. A secondary standard of spectral radiance is needed to transfer the calibration of the primary standard to the crossed beam apparatus, since the size and intensity of the primary standard are incompatible with the crossed beam apparatus. The stable point source used in the relative calibration phase is not suitable as a secondary standard because of the inherent difficulties in comparing a point source to the primary standard.

A secondary standard of spectral radiance has been developed that is suitable for comparison with the primary standard and is also compatible with the crossed beam apparatus. It is compared with the primary standard on an absolute spectral basis in a special dark room arrangement. There the photon outputs from equal areas of the two sources into equal solid angles are compared for various wavelengths selected by a monochromator. A photomultiplier operated in the counting mode serves as a linear detector for this comparison. The resulting absolute calibration of the secondary standard is specified by the absolute spectral

distribution of photons emitted per unit time, per unit area, into unit solid angle. This knowledge permits use of the secondary standard to simulate a planar source of photon radiation with known spatial and spectral densities that is isotropic, provided the photon radiation from the secondary standard is isotropic over at least the solid angle subtended by the detector.

Transference of Absolute Calibration to Detection System with Secondary Standard. The secondary standard calibration is stated in such terms that it can be used to simulate, for the optical detection system, a planar distribution of isotropic photon radiators of known spatial and spectral densities. The absolute photon detection efficiency is calculated from the detection system responses to this simulated distribution of isotropic photon radiators in the collision volume, using the two narrow band interference filters.

The calculation is performed by matching the two observed detection system responses to theoretical expressions involving the two unknown constants needed to render the photon detection efficiency absolute. Spatial variations are included in the calculation by integrating the relative calibration factor $n(x,y,z)$ over the location of the secondary standard in the collision volume. Spectral variations are included in the calculation by integrating over the product of the secondary standard spectrum times the spectral response of the detection system, which is assumed to vary according to the narrow band filter spectral transmittance times a slight linear variation due to the photomultiplier characteristics. Two constants are required in this determination to simultaneously introduce that slight linear spectral variation and render the

overall photon detection efficiency function absolute.

Measurement of Photon Rate S

The measurement of the photon rate S in Equations 3 and 4 is made very difficult by the background noise consisting of stray light, light from hot surfaces in the sources, and photomultiplier dark current. This noise is reduced as much as possible by extensive shielding and by cooling the photomultiplier. The signal is made as large as possible by using the greatest electron current consistent with small space charge blow-up of the beam. The resulting signal-to-noise ratio is approximately 10^{-3} to 10^{-4} over the range of energies used.

Signal photons are distinguished from noise by modulating the beams at different frequencies while the photomultiplier pulses are switched between two scalers in such a way that both scalers receive noise counts but only one receives true signal counts. The indicated signal is then taken as the difference in the readings of the two scalers. This indicated signal differs from the true signal by the amount that the noise pulses registered by the two scalers differ; therefore, the difference in noise received by the two scalers is called false signal.

The detection problem is treated statistically in Appendix III. There it is shown that the false signal has zero mean. A reasonable deviation from that mean is the standard deviation of the false signal, which is found to be $\sqrt{NT}$, where N is the average noise rate and T is the time interval used for counting. Unfortunately the mean ST of the true signal (where S is the average true signal rate) compares unfavorably with this typical error of $\pm \sqrt{NT}$ for reasonable values of T . In Appendix III a quality factor Q is defined by the ratio $ST/\sqrt{NT}$ and a

graph is presented that gives the statistical interpretation for various values of Q .

Form Factor Determination

The form factor F in Equation 5 is evaluated by the method of scanning the beams simultaneously with coplanar slits, which has been found satisfactory by Bacon³ and others.^{2,24,25} This method is illustrated in Figure 3. From the beam profiles thus measured, the integrals in the form factor are approximated by finite sums as in Appendix I. As a check on the beam profiles revealed by the scanning slits, the beams can also be scanned by the edge of the plate containing the slits. The results of this latter scan are differentiated to obtain the profiles needed to calculate F . If the beam profiles are sufficiently disturbed by the plate to affect the value of F , the form factors obtained by these two methods will differ.

Relation of Measured Emission Cross Sections to Excitation Cross Sections

The measured cross sections represent the emission of photons of the wavelengths $4554 \text{ \AA}$ and $4934 \text{ \AA}$ from Ba^+ ions excited by electron impact. Reference to the ionic energy levels in Figure 1 shows that the number of excitations from the 6S ground state to the 6P states can differ from the number of photons emitted in downward transitions for two reasons: (1) the 6P levels can be populated by electrons cascading from higher levels, and (2) an electron excited to a 6P level could make a downward transition to the 5D levels instead of the 6S ground state.

Figure 3. Determination of Beam Profiles with Slit Scanner

However, no evidence of cascading was found by investigations made in this experiment. The branching ratios measured by Gallagher²⁶ are applied to account for the downward transitions from the 6P states to the 5D states instead of the 6S ground state. In this way excitation cross sections can be deduced from the measured emission cross sections.

Cascading was shown to be negligible by measuring at 8 eV with a 3892 Å narrow band filter in the optical path of the detection system. It can be seen in the energy level diagram in Figure 1 that this wavelength corresponds to a transition to the 6P states from the 6D states, which can be excited from the ground state with an energy of 8 eV or more.

CHAPTER III

APPARATUS

Crossed Beam Apparatus

The arrangement of the components of the crossed beam system is shown in Figure 4. This apparatus is fixed to an experiment plate, which is in turn suspended within the ultrahigh chamber from the chamber top cover. The electron beam is produced in a hybrid Pierce-type gun with pulsed heating, and the beam is collected for measurement and energy analysis after it intersects the ion beam in the collision volume. The ion beam is produced in a surface ionization source, separated from Ba neutrals and ion source light in an electrostatic analyzer, and collected after intersecting the electron beam.

The collision volume defined by the intersection of the two beams is viewed through the port by a photomultiplier located along the z-axis in Figure 4. Precautions are taken to ensure that the collision volume is field free. The overall view in Figure 5 shows the chamber and associated electronics.

Vacuum System

The vacuum chamber is in the form of an all stainless steel cylinder of 21 inches inside diameter and 6 inches inside depth. The top cover is sealed to one end of the cylinder by compressing a soft aluminum o-ring between the top cover and a flange on the cylinder. Three electrical and water feedthroughs are mounted in a similar fashion on the top

Figure 4. Schematic Diagram of Crossed Beam Apparatus

Figure 5. Vacuum Chamber and Electronics

cover. The viewing port is mounted on the top cover with a Varian "Con-flat" flange. The chamber is pumped through a molecular sieve trap by a four inch oil diffusion pump with water-cooled chevron baffle, in tandem with a mechanical forepump. The entire system is bakeable to temperatures limited by the gold o-ring on the trap and the aluminum o-rings on the chamber top. Details of this system can be found in the thesis of W. C. Lineberger.²⁷

The trap and chamber are baked at 370°C and 170°C, respectively for 48 to 72 hours. The ion source is heated slowly during this time and run at full power at least 12 hours before bakeout ceases. The electron source is heated slowly and operated at full power at least 3 hours before bakeout is removed. The chamber cools to ambient temperature in 36 hours, and the pressure is then found to be approximately 8×10^{-8} torr with both beams on.

Electron Source

Measurement of the emission cross sections for impact energies near threshold in this experiment required development of an electron source producing a beam with energy spread much smaller than the lowest energy used, 2.5 eV. A modified 6L6GC beam power tube was used by Bacon³ to make measurements at 8 eV to 98 eV with a measured beam energy spread from the oxide cathode of approximately 2 eV. Previous experiments requiring an electron beam with small energy spread have employed electrostatic energy analyzers as part of the electron source.²⁸⁻³² For this experiment it was necessary to improve approximately three orders of magnitude on the currents previously reported from such sources. Con-

siderable effort was expended in this manner toward establishing an electron beam that had maximum current consistent with reasonable shape and energy spread. Success was limited to an improvement in current of only approximately two orders of magnitude over previously reported sources of this type.

Attempts were made to obtain an electron beam with reduced energy spread by using an oxide coated cathode with less oxide material. To avoid increase in beam energy spread due to heating voltage, a pulsed heating system was developed in which heating voltage is impressed across the cathode only during that part of the electron beam pulsing cycle when no current is being drawn. Trial of such an electron source using a 2E24 beam power tube demonstrated that voltage across the directly heated cathode did introduce an energy spread in the beam which was removed by this scheme of pulsed heating. However, there remained a measured spread of 2 eV in the beam energy even with the reduced amount of oxide material.

The final electron source adopted was a hybrid version of the Pierce gun, employing a thoriated iridium filament. A diagram of this source as seen from the edge is presented in Figure 6. Plate 1 is held at a potential below that of the filament; plates 2 and 3 are at increasing potentials to provide successive stages of acceleration. The shapes of these plates conform to the equipotentials shown by Pierce³³ to exist in the charge-free region outside a rectilinear beam that is space-charge-limited. Therefore, that portion of the electron source is known as a Pierce gun.

The electron beam in Figure 6 is decelerated between plates 4 and

Figure 6. Diagram of Electron Source

5. These latter two plates actually have the shapes appropriate for acceleration without space charge blow-up, but they are instead reversed to decelerate the beam without space charge blow-up. It was discovered that this behavior can be predicted using Pierce's theory.

The electron beam is produced by this hybrid Pierce gun as follows. The conventional Pierce gun, composed of the filament and first three plates, emits a well defined beam, with energy above that desired, into the field-free region between plates 3 and 4. This beam is decelerated between plates 4 and 5 so that it enters the collision volume with the desired energy. This source has three primary advantages: (1) it delivers maximum current attainable with the desired beam energy; (2) without diminishing the current, it removes the filament from the collision volume, thus reducing the amount of light from the filament seen by the detector; and (3) the shape of the last plate of the deceleration portion permits placing it flush against the wall of the electron housing, which is not possible with the conventional Pierce gun plates.

The assembly of the electron source is shown in Figure 7. Plate 1 is stainless steel, while the others are copper. After the plates were formed to the prescribed shapes of equipotentials, wax impressions were made of them to check the symmetry of the shapes about the slits and to provide guidance in corrections. This was necessary so that no asymmetry would tend to deflect the beam off its intended axis through the slits. The plates were assembled with a guide bar aligning the slits, using ceramic spacers between the corners of adjacent plates.

The thoriated iridium filament (Veeco Part No. 1220-003) was spring loaded between tabs appropriately located on Plate 1, as shown in Figure 8.

Figure 7. Electron Source Plate Assembly

Figure 8. Electron Source Filament Mounting

The ceramic insulating tube was purchased from the Norton Company. The tungsten springs were obtained from CUE38111-A, VT-4-C, and CUE838 transmitting tubes. Stainless steel 0.003 inch thick was spot welded between each end of the filament and its spring as a clamp. The filament was clamped in place with the springs under temporary compression so the filament would be left under tension. The current leads were formed by squeezing the curled ends of no. 14 gauge wires into washers, which are held against the springs by the compression of the latter.

The electron beam is pulsed on and off with a 50 percent duty cycle by adding an appropriate square wave voltage to the potential on plate 2. Heating voltage is impressed across the filament only during the "off" part of the electron beam cycle. The repetition rate must be sufficiently high for the filament to retain the proper temperature for thermionic emission during the "on" part of the beam cycle. One end of the filament is held at a negative voltage corresponding to the electron energy desired in the collision volume, since this region is at ground. Therefore, the entire filament is at the correct potential during the "on" time for the electron beam. This filament potential is obtained from a Harrison Model 6116A d.c. supply, which has an accuracy of 0.1 percent plus one millivolt. During the segment of the pulsing cycle when the beam is off the polarity of the heating voltage across the filament is such that it raises the potential along the filament, thus helping to turn off the beam.

The electron source is enclosed by a stainless steel housing with an exit hole only for the beam. The inner walls of the housing and plate 5 are coated with acetylene soot to reduce escape of light from the filament by reflections. The slits in the electron source allow light from

the filament to diverge only enough so that a small fraction strikes the aperture plate on the sides of the aperture, and that region is coated with soot also. The remainder of the light escaping from the electron source enters the electron cup.

Electron Beam Measurement and Energy Analysis

After intersecting the ion beam, the electron beam is collected in the cup shown in Figure 9. An aperture plate is located in front of the cup for detecting electron beam blow-up. With no suppressor voltage applied inside the cup, a sample of the beam is passed through a slit in the back of the cup and into the 127° energy analyzer.

The system and its operation are described in detail by Bacon.³ In this experiment the electron currents are one to two orders of magnitude smaller than those of Bacon. This necessitated replacing the small collector at the analyzer exit by a faraday cup with a grounded shield completely surrounding the cup and its lead. To achieve this addition in the limited space of the vacuum chamber, it was necessary to rotate the energy analyzer 90° about the axis from the orientation used for pictorial convenience in Figure 9.

The electron current is collected with a positive suppression voltage in the cup. The current is smoothed by a low pass filter and determined by measuring the voltage across a precision 1000 ohm resistor carrying the current. This voltage measurement is performed with a Keithley Model 149 Milli-microvoltmeter.

Ion Beam Apparatus

The ion source produces Ba^+ ions by ionizing Ba neutrals on hot rhenium.^{3,9,14,16} The source is an extensively modified version of the

Figure 9. Electron Cup and Energy Analyzer

one developed by Bacon.³

Barium neutrals are obtained by heating barium metal to approximately 600°C in a cylindrical molybdenum crucible. This container is mounted inside a heated copper block by direct contact with the block at the mouth of the crucible. The block is heated by an internal tungsten wire coil insulated from the block between concentric ceramic cylinders. The typical power input to this coil is 30 watts.

The copper block and crucible top are firmly attached to a pair of iron blocks which are clamped over one end of the ionizing rhenium filament. Barium neutrals from the hot crucible are guided by a one-eighth inch tube through the filament block and are sprayed toward the center of the ionizing filament through an appropriately slanted slit 0.02 inch wide.

The rhenium ionizing filament is clamped between iron blocks at both ends. A current of typically 18 amperes is conducted through the blocks to heat the ionizing filament to approximately 1800°C.

The ionizing filament is held at a potential above ground corresponding to the ion energy desired in the collision volume, which is at ground potential. This voltage is provided by a Fluke Model 413D voltage supply having an accuracy of 1.25 percent. The ions formed at the hot filament are accelerated by the source optics diagrammed in Figure 10. The repeller electrode is held at the potential of the filament, while the extraction electrode is held approximately 45 volts below that potential. The shapes of these elements are chosen so that the field between the extraction electrode and the filament and repeller electrodes forms the ions into a rectilinear beam. The beam experiences one more

Figure 10. Schematic Diagram of Ion Source Optics

stage of acceleration to the desired energy beyond the extraction plate. The last region the beam traverses in the source itself is field-free, with collimating slits at each end.

The ion source is enclosed by a water-cooled copper cylinder. Three turns of one-fourth inch copper tubing are brazed on the outside of this cooling jacket.

The ion beam leaves the cooling jacket through a slit and continues through a short stainless steel tube into an electrostatic energy analyzer,³⁴ as shown in Figure 4. Plates for controlling the vertical deflection of the beam are located in this tube. The ion beam enters a slit in the grounded case of the analyzer, which is oriented 45° to the beam. A positive voltage on the plate inside the analyzer deflects the ion beam 90° and out an exit slit in the analyzer case. Light and neutrals pass instead through a grid on the inner analyzer plate and are trapped. The voltage for the analyzer is obtained from a 10-turn potentiometer with the ion acceleration voltage across it. Since the analyzer voltage should always be a certain fraction of the acceleration voltage, this simple device requires little adjustment and replaces a precision high voltage supply.

The ion faraday cup is six inches deep and has a rear surface inclined to the beam. A plate with -300 volts is located deep in the cup, providing a transverse field to prevent charged particles from leaving by the entrance aperture. This cup has been demonstrated to be 100 percent efficient in retaining reflected and secondary charged particles.³ The ion current is measured with a Keithley Model 417 picoammeter, which has an accuracy of ± 2 percent.

The ion cup is held at -67 volts to repel stray electrons. A grounded plate shields the collision volume from the potential on the cup. The aperture in this plate is sufficiently large so that none of the ion beam strikes the plate in operation. All ion beam optics after the ion source are those used by Bacon, and details may be found in his Ph.D. thesis.³

The water and currents for the ion source are brought into the vacuum chamber by feedthroughs mounted on a stainless steel flange four inches in diameter. The flange is sealed with a soft aluminum o-ring. Currents for the source filament and oven are conducted by four Advac Type 375-ES cable end seals heliarc welded in appropriate holes in the flange. Cooling water is carried by two one-fourth inch stainless steel tubes heliarc welded through the flange. These stainless steel water tubes are connected inside the vacuum chamber to the copper tubing on the source cooling jacket by Cajon Type VCR⁴ high temperature ultrahigh vacuum fittings. Seals are effected in these fittings by crushing a nickel gasket between knife edges.

It is possible that some of the ions produced in this surface ionization source could be in excited states above the $6S$ ground state. Considerable evidence that this does not affect the results is provided by the disappearance of signal, within experimental error, for impact energies below the threshold energy for excitation of the $6^2P_{3/2}^0$ level from the $6^2S_{1/2}$ ground state. The effect of having ions excited to the $5D$ or higher levels would be to produce signal at energies as low as 0.6 eV below excitation threshold.

The purity of the ion beam was checked on a magnetic sector mass

spectrometer by Bacon.³ He detected some sodium and potassium ions emitted by the rhenium filament, but this contamination was found to represent less than 0.1 percent of the total ion current. This contamination does not contribute to the observed signal, and the error of less than 0.1 percent in ion current measurement is negligible.

Beam Current Regulators

A circuit was developed for this experiment which replaces the human operator in the typical experimental situation where some voltage adjustment is required to correct for variations in the beam current observed with a meter. It uses the voltage at the recorder output of the current-measuring meter to detect any drift and then corrects this variation with an appropriate change in the voltage used for that purpose. The meter output remains completely isolated electrically from the correcting voltage. The current-measuring meter adapts the system to the range of currents to be controlled. The regulating circuit is adaptable to the range of correcting voltages used.

A simple version of the regulator that was found to work well is shown in Figure 11. The connection of Figure 11(a) is used when an increase in controlling voltage produces a decrease in beam current; the connection in Figure 11(b) is used when an increase in controlling voltage produces an increase in beam current.

In either case in Figure 11, a change in beam current produces a change in light output of the bulb, and therefore the resistance of the photocell in the voltage divider is altered. This causes the output voltage to increase or decrease, depending on whether it is taken from the photocell or from R_c . The regulated/unregulated switch is open for

Figure 11. Beam Current Regulator Circuits

regulation of the beam current and closed to disable the automatic regulation and allow manual adjustment with the power supply providing voltage V_c . The capacitor introduces phase shift to avoid oscillations.

The value of R_B is set so that the meter output voltage at the desired beam current causes the light bulb to operate at a reasonable level. The resistance of R_C is then set to the same order of magnitude as that of the illuminated photocell. R_B is readjusted to give the exact current desired with this choice of R_C . The voltage V_c must be set larger than the greatest output voltage needed. By empirically adjusting the values of R_B and R_C , one can obtain different response speeds and degrees of damping due to the different operating points of the light bulb-photocell transducer. The response time was found to be on the order of 0.1 second.

In this experiment the circuit of Figure 11(a) was used with the 2E24 beam power tube by applying the output voltage to the control grid and using the 0-10 volt recorder output of the Keithley 149 Milli-microvoltmeter. The circuit of Figure 11(b) was used to regulate current from the hybrid Pierce electron gun because the output voltage was applied to plate 2 in the gun, where current was increased by an increase in voltage. A similar circuit was built and tested for regulating the ion beam, but its inherent stability did not usually warrant use of the regulator.

Photon Detection System

The system for collecting photons of the desired wavelength from the collision volume is shown in Figure 12. A thermoelectric cooler containing the photomultiplier is rigidly attached above the light-tight filter slide.

Figure 12. Photon Collection System

The double convex lens in Figure 12 consists of two plano-convex lenses, each having a diameter of 42 mm and a focal length of 55 mm. This lens is held in a stainless steel assembly which is mounted securely to the experiment plate in a properly aligned position. Light collected by this lens passes through the window in the chamber top and is focused in an image approximately one inch above the window. The window is a Granville-Phillips one and one-half inch diameter model with a 2 mm thick Pyrex glass.

A light-tight aluminum block outside the window houses a single plano-convex lens identical to those inside the vacuum chamber. It is located one focal length above the image formed by the first lens so that light from the collision volume will pass straight through the narrow band filter for selection of the desired wavelength.

The narrow band interference filter for the desired wavelength is placed in a light-tight slide³⁵ and introduced into the optical path without admitting room light. The filters were obtained from Thin Film Products, Inc. and they were calibrated in the optical calibration phase of the experiment. The pass bands are approximately 100 Å wide, with a transmission in the center of this band of approximately 65 percent.

The polarization fraction was determined by comparing signal count rates with the axis of a linear polarizer oriented first parallel and then perpendicular to the electron beam as discussed in Chapter II. For this purpose a Bausch & Lomb Type HN32 linear polarizer was cut to the size of a narrow band filter. This polarizing disc was placed, with the appropriate orientation, underneath the filter in the light-tight slide.

The EMI 9584S photomultiplier tube and RIDL Model 10-17 preamplifier are housed above the filter in a thermoelectric cooler Type TS-104, made by Products for Research. Pulses from the photomultiplier are processed by an RIDL Model 33-13A linear amplifier and pulse height analyzer. The output from the pulse height analyzer is divided in time between two RIDL Model 49-25 timer-scalers by the modulation system.

Modulation System

The modulation system requires a scheme to divide the processed signal from the pulse height analyzer between two scalers so that they receive statistically similar samples of the noise while only one scaler also counts signal. The modulation system also consists of the circuitry to modulate the beams and perform time division of pulses to realize this scheme. Circuit limitations in the modulation system used by Bacon from 8 eV to 98 eV³ would not correctly separate signal and noise in this experiment, where the signal-to-noise ratio is one to two orders of magnitude smaller.

The modulation scheme must chop the two beams and switch the processed photomultiplier pulses so that one scaler counts when both signal and noise are present, and the other scaler counts when only noise is being detected. Figure 13 presents an account of the signal and noise produced with the various states of the two beams. The noise N_e that is correlated only with the electron beam is primarily due to simultaneous ionization and excitation of neutral barium by the electrons. The noise N_i which is in phase only with the ion beam is attributed to photons produced when the ion beam interacts with background gas. The background noise N_b is not correlated with either beam because it is due to background

Figure 13. Occurrence of Signal and Noise Components in Modulation Sequence

light and photomultiplier dark current.

The waveform that switches the received pulses between the scalars should have a 50 percent duty cycle so that the two scalars count noise for the same length of time. The components of noise present with various beam states shown in Figure 13 require that the signal-plus-noise scaler should count when the two beams are in like states, while the noise-alone scaler should count when the beams are in unlike states. The inevitable conclusion from these considerations is that the three waveforms designating the two beam states and scaler operations must be related in one of the three modes shown in Figure 14. The scheme in Figure 14(c) is used in this experiment to ensure that the two scalars see identical states of the light from the pulsed electron heater, which could be correlated with the electron beam switching waveform. Except for this consideration, any of the schemes in Figure 14 is satisfactory.

The modulation scheme of Figure 14(c) is realized by the circuitry shown in Figure 15. The beam and switch waveforms are derived from integrated circuit J-K flip-flops run synchronously with repetitive clock pulses. The ion flip-flop and the switch flip-flop toggle respectively on the downward and upward transitions of the electron flip-flop. The phase-maintaining gate is necessary to put the ion and switch waveforms in the phase relation in Figure 14(c); otherwise, it would be possible for the ion waveform to lead the switch waveform by 90° or vice versa. With the ion beam waveform leading the switch waveform, the signal would appear on scaler 2 instead of scaler 1. If the phase between the ion and switch waveforms slip into this undesired mode, the phase-maintaining gate

Figure 14. Alternative Modulation System Waveforms

Figure 15. Modulation System Diagram

immediately pulses the reset terminal of the ion flip-flop and restores the proper phase. The ion flip-flop, rather than the switch flip-flop, is used for this correction to avoid disturbing the critical switching of background noise between scalers.

The clock pulse is obtained from a General Radio Model 1217-C pulse generator set for pulses 100 nanoseconds wide. The pulse rise and fall times are less than 10 nanoseconds. The flip-flops toggle on a threshold during the downward transition of the clock pulse with transition times of less than 100 nanoseconds. The gates used have typical delay propagation times of 50 nanoseconds.

The remainder of the pulsing circuitry components in Figure 15 serve as buffers. The clock pulse is gated twice at the input. The beam chopping waveforms are amplified to amplitudes sufficient to control the beams. Emitter follower circuits transmit pulses coming in from the pulse height analyzer and pulses going out to the scalers. The electron filament heater is controlled by a circuit with an emitter follower, transistor amplifier, and transistor switch.

Absolute Calibration Apparatus

The absolute optical calibration of the photon detection system requires comparison of a secondary standard with a primary standard of spectral radiance, and transference of the calibration to the photon detection system. A separate experimental determination of the spatial variation of photon detection efficiency is also required.

Relative Calibration Apparatus

Relative calibration consists of determining the relative spatial

variations of the photon detection efficiency with the position where the detected photons originate. This is determined from the response of the photon detection system to a stable point source of light placed at precisely known positions in the collision volume.

The output of this point source must not change appreciably with time, temperature, or exposure to room light. Its radiance must fall in the narrow range where it is sufficient to be easily detected in background light but low enough to stay within the operating range of the extremely sensitive detection system. The emission should be isotropic at least over the solid angle subtended by the lens system for all positions of the point source.

Extensive tests on incandescent sources small enough to be moved around the collision volume indicated that the stability of such sources is inadequate. Lack of stability in detector sensitivity, noise, geometry, optical transmission, and electrical input were experimentally eliminated as the cause of the indicated instability, because in each case the parameter was either carefully controlled or its variations were not correlated with the undesired variations in indicated source intensity. Consequently, a different type of light source was developed for the relative calibration.

The source shown in Figure 16 was developed specifically for the relative optical calibration. It is mounted adjacent to the collision volume with the light source at the end of the brass tube protruding into the collision volume, facing the lens. The brass tube is threaded to allow vertical motion; horizontal movement is achieved by screwing the

Figure 16. Point Source for Relative Optical Calibration

arm holding the tube into one of six different positions on the bracket.

The source inside the tube is a capsule of radioactively excited phosphor. Tissue paper covers the capsule to improve the isotropy of the source. A metal disc with a pinhole in the center is pressed over the tissue to define a point source. A microscope slide glass is cemented at the edge of the tube to protect the source from dirt. The washer protruding slightly beyond the glass seal protects it from unintentional contact.

The light source is turned "off" for assessment of background noise by rotating the rubber shutter over the source from a position well outside the collision volume. This is done from outside the darkened chamber by actuating the electromechanical shutter arm. Analysis of the data revealed no correlation between the signal and the noise determined with this shutter. Since the signal was several times larger than the indicated noise, this is taken as evidence that the shutter performed properly.

The stability of the radioactive phosphor source was checked in several ways. The count rate it produced in the detection system was monitored in short intervals over a period of two days and found to deviate only two and one-fourth percent from the mean. Heating the source to approximately 50°C had no effect on the indicated emission. Exposure to normal ambient light had no effect on the output. Direct exposure to sunlight for five minutes did increase the indicated count rate by 10 percent, but it returned to the normal value with a time constant of 47 hours.

Dark Room Absolute Calibration System

The absolute calibration phase required the absolute filter transmittances and the calibration of a small light source in terms of its absolute spectral radiance, as explained in Chapter II and Appendix II. The various components are aligned on a heavy optical bench $11\frac{1}{2}$ feet long. The entire apparatus is located in a dark room that is 21 feet by 36 feet and has a ceiling 10 feet high. Openings to the room are sealed with opaque covers and light-tight gaskets. A black polyethylene curtain and a door form a "light lock" by which one may enter the room without admitting excessive light. A small flashlight with a red narrow band filter is used only between measuring periods to perform manipulations of the apparatus without overly exciting the photomultiplier. The exact arrangement and use of the various components are described in Chapter IV. The individual components are described in the following sections.

Primary Standard of Absolute Spectral Radiance. The photon measurement is made absolute for this experiment by the most direct comparison with the National Bureau of Standards that is available to individual laboratories. The ultimate standards of absolute spectral radiance are blackbody sources such as those maintained at the National Bureau of Standards. This agency calibrates lamps as shelf standards by comparison with blackbodies. Working standards are then compared with the shelf standards and issued to certain government agencies and a few private laboratories selected as distributors of the calibration to other laboratories.

The lamp used to disseminate the calibration from the N.B.S.

blackbody was developed for that purpose at the National Bureau of Standards³⁶ and is manufactured by General Electric as Type 30A/T24/17. It is shown in Figure 17. The ends of the tungsten ribbon filament are bent back in the SR8A configuration so that only the uniform temperature region in the center is viewed. The central portion is made flat to avoid polarization of the light emitted from the window.^{36,37} The fused silica viewing window is removed from the filament by four inches to avoid evaporation of tungsten on the window. The large volume of the envelope prevents the excessive fluctuation of convection that would make the light output unstable. The 30A/T24/17 lamp used in this experiment was calibrated at 25 amperes (r.m.s.) by Eppley Laboratories and bears their serial number EPS-1047. In this experiment it is referred to as the primary standard of spectral radiance.

The standard lamp is run in this experiment at the calibration current by an EG&G Model 590 Calibrated Lamp System, designed specifically for accurate reproducible operation of tungsten lamp standards. It provides an alternating one kilohertz square wave with the r.m.s. value of the current automatically regulated within one-fourth percent of the value selected on a three-place digital dial. The light-tight housing in Figure 18 holds the lamp in a well defined position so that only the filament is visible outside. Inside the housing, dull black corrugations prevent reflections and forced-air ventilation maintains the environment of the lamp at room temperature.

Secondary Standard of Spectral Radiance. The secondary standard of spectral radiance is calibrated by direct comparison with the primary

Figure 17. Primary Standard of Absolute Spectral Radiance

Figure 18. Primary and Secondary Standards of Absolute Spectral Radiance

standard, and the former is operated in the collision volume of the crossed beam apparatus to calibrate the optical detection system. For this experiment a new light source was developed as a secondary standard; the stable point source devised for the relative calibration was not used for this purpose because its small area precluded accurate comparison with the primary standard. The size of the secondary standard chosen made it compatible with both the dark room facility and the collision volume of the crossed beam apparatus. The intensity and spectrum of the secondary standard were also suitable both for comparison with the primary standard and for exciting the photon detection system.

The secondary standard is shown in Figure 18 with the primary standard. The former source consists of a General Electric EL101G Type F electroluminescent panel. The dimensions of the exposed region in the central portion of the panel are made identical to those of the primary standard filament so that any aberrations in the optical system will not produce different behavior of the comparison system with the two sources. The panel is excited by a Sorenson Model 2000S voltage regulator and an intermediate step-up transformer, at 250.6 volts r.m.s. The supply had a regulation of 0.1 percent and the voltage was checked regularly with a 0.25 percent electrodynamicometer meter. It was found that the stability of light output with variations in voltage was improved by at least a factor of two in using double the rated voltage of 120, and the stability obtained with this electrical input was comparable to that of the standard lamp.

The emitting surface of the secondary standard was demonstrated

to be homogeneous within two and one-half percent. To determine this, an image of the source was formed on a pinhole to select a small region for viewing by a photomultiplier, which received only the light selected by the pinhole. The source and lens were moved together to select the region thus viewed. Noise due to background light and photomultiplier dark current was measured and subtracted at each step by blocking only the light entering the pinhole that came straight from the source.

The isotropy of the emission of the secondary standard was checked with the same system used to study the homogeneity. The source was kept on the lens axis but it was rotated so the normal to the emitting surface made various angles from 0° to 30° with the lens axis. Noise was again measured and subtracted at each angular position. The count rates indicated by these measurements differed at most by three percent, and no systematic variation of emission with angle was observed. Therefore, the output of the secondary standard was judged to be acceptably isotropic over the solid angles to be used. Similar results were obtained when the emitting surface was covered by a calibrated neutral density filter for use in the collision volume of the crossed beam apparatus.

Monochromator. The grating monochromator used in the dark room to isolate individual wavelengths selects a portion of the image formed over its entrance slit and presents a monochromatic reproduction of that portion at the exit slit. This experiment employs a Jarrell-Ash Model 82-410 0.25 meter Ebert monochromator, which contains a grating with 1180 lines per inch and a $6000 \text{ \AA}$ blaze. The 100 micron-wide slits provide a resolution of five Angstroms. In this experiment mercury and zinc lamps were

used to calibrate the monochromator to within one Angstrom of the 4358.34 Å and 5460.74 Å lines of mercury and the 4722.16 Å line of zinc. Precision in selecting the wavelength was increased by adding a more precise pointer to the dial. Backlash effects were avoided by always turning the dial in the same direction during spectral measurements.

Miscellaneous Optics. A high quality concavo-convex lens is used to form images of the standards on the monochromator entrance slit. It has a diameter of three and one-half inches and a focal length of approximately 24 inches. The opaque surface in which the lens is mounted allows light from the source to enter the acceptance angle of the monochromator only through the lens.

The narrow band interference filters are also mounted on the optical bench in an opaque surface which allows only light through the filter to fall in the acceptance angle of the monochromator. A completely opaque surface could also be mounted to block only the beam in the monochromator acceptance angle, allowing all other light detected by the photomultiplier to be measured as background noise.

Two neutral density filters with absolute spectral transmittance calibrations provided by Eppley Laboratories are available for introducing a known attenuation in cases where the photomultiplier otherwise receives too much light to be operated in the counting mode. This attenuation is approximately 10^4 and is independent of wavelength over the visible range.

CHAPTER IV

EXPERIMENTAL PROCEDURES AND RESULTS

The application of the experimental techniques previously discussed requires a variety of procedures. In this chapter the experimental procedures are presented under the two categories of absolute optical calibration and cross section measurement, since those were the two areas of major effort.

Absolute Optical Calibration

Absolute optical calibration is the experimental determination of the fraction of photons radiated isotropically from the collision volume that are registered as counts in the detection system. This information must be expressed as a function of the wavelength of the photons, the position in the collision volume where they originate, and the specific narrow band interference filter employed in the detection system.

The experimental technique, explained in detail in Chapter II, segments the desired function into two factors involving wavelength only and a factor involving position only. The experimental technique for finding the component factors and the overall amplitude of the absolute photon detection efficiency is summarized in Figure 19. The experimental procedures diagrammed in that figure are discussed in this chapter.

Figure 19. Diagram of Steps in the Experimental Determination of the Absolute Photon Detection Efficiency in the Forms $N_{4554}(x,y,z,\lambda) = (a\lambda+b) n(x,y,z) F_{4554}(\lambda)$ and $N_{4934}(x,y,z,\lambda) = (a\lambda+b) n(x,y,z) F_{4934}(\lambda)$.

Relative Optical Calibration

The relative optical calibration constitutes determination of that function of space which represents the relative sensitivity of the detection system to photons originating at different locations in the collision volume. This information is contained in a function $n(x,y,z)$. The amplitude chosen for $n(x,y,z)$ is of no consequence in the final calibration results because the amplitude of the final result is later matched to experimental observations.

The relative spatial variation was found by taking the response of the detection system to a point light source located at various known positions in the collision volume. The relative calibration apparatus described in Chapter III was used for this purpose. It consisted of a point source of radioactively excited phosphor, which could be turned "off" by covering it with an electromechanical shutter.

The point source was located at 30 different positions in the x-z plane designated by six different values of x and five different values of z covering the collision volume and adjacent points. Variation with y , which corresponded to the width of the ion beam, was negligible because of the limited extent of the collision volume in that direction.

At each position the background noise was carefully assessed by comparing the detection system responses with the source both covered and uncovered. The chamber was not disturbed between such measurements. The noise was measured both before and after each observation with the source uncovered. The system response to the source alone was then taken to be the response with the source uncovered, minus the response with the source covered.

For each vertical position a measurement of 20 minutes' duration was made on each horizontal position, and then the entire procedure was repeated for a new vertical position. Horizontal scans were made for each vertical position in this manner at least six times, spread over a period of at least one month. For each position the various values obtained in the above manner differed approximately 10 percent.

A different type of scan was made by moving vertically over all grid points associated with only one horizontal position. Five repetitions of this scan agreed within two percent. Each horizontal scan was then normalized to this vertical scan at their common point.

The relative calibration results are listed in Table 2. The values are normalized to the value at vertical position 0" and horizontal position #3 arbitrarily, since the amplitude chosen for the function $n(x,y,z)$ has no effect on the final amplitude of the calibration result.

Table 2. Relative Calibration Results

horizontal position $\rightarrow$ ($\frac{1}{4}$ " spacing)						
vertical position	#0	#1	#2	#3	#4	#5
$+\frac{1}{4}$ "	0.0472	0.5881	1.1296	1.0513	0.8425	0.1626
$+\frac{1}{8}$ "	0.0684	0.6183	1.0726	1.0200	0.8360	0.2329
0"	0.1063	0.6636	1.0637	1.0000	0.8162	0.2667
$-\frac{1}{8}$ "	0.1192	0.6452	1.0178	0.9708	0.8171	0.3596
$-\frac{1}{4}$ "	0.2151	0.6113	0.9919	0.9476	0.7930	0.3876

The relative calibration results are presented graphically in Figure 20. There it can be seen that the photon detection efficiency is not a strong function of position over the actual collision volume. It was found that the various curves for $n(x, z_1)$ could be made identical by normalizing the system response of each and stretching the x scale of each about the geometrical axis of the lens system in proportion to the distance from the lens. The slight asymmetry about the axis was attributed to a tilt in one lens.

Calibration of Secondary Standard of Absolute Spectral Radiance

The electroluminescent panel used as a secondary standard of spectral radiance was calibrated against the tungsten ribbon primary standard of absolute spectral radiance in the dark room facility shown in Figure 21. The components of this apparatus are described in detail in Chapter III. An opaque polyethylene curtain bisected the room into optically isolated parts. Linear photon detection was achieved through operation of the photomultiplier in the counting mode as it viewed only the monochromator exit slit from a distance of 15 feet.

To compare the spectral radiances of the primary standard and secondary standard the two sources were alternately placed on the optical bench with their emitting areas in the same position. A neutral density filter over the aperture of the primary standard housing introduced a known attenuation. This filter was absolutely calibrated by Epply Laboratories. The concavo-convex lens formed an image of the source under observation over the monochromator entrance slit, which was much smaller than the image itself. In this way only a well determined

Figure 20. Graph of Relative Calibration Results

Figure 21. Dark Room Calibration Facility

area of the central portion of the image was accepted. The monochromator presented a monochromatic reproduction of the illuminated entrance slit at its exit slit. The photons leaving the exit slit were counted by a photomultiplier shielded from all other sources of light.

Background noise was determined and subtracted from the previous measurement by counting the photomultiplier pulses with the opaque surface blocking only the light beam directed at the monochromator entrance slit from the lens. Therefore, the noise measured included all background noise such as photomultiplier dark current, background room light, light from the source under observation leaking around the large opaque curtain, and light transmitted by the monochromator that was not originally part of the source image at the entrance slit.

The spectral radiance is a function of wavelength which gives the number of photons that are radiated per second from unit area into unit solid angle and have wavelengths in an interval one Angstrom wide centered at the specified wavelength. Thus it can be seen that the signals obtained in the above manner effected a comparison of the two standards in terms of their spectral radiances. In this comparison method the two sources were observed with identical optics. Equal emitting areas were selected by the monochromator entrance slit. Equal solid angles were subtended by the collecting lens. Selection of a portion of the spectrum by the monochromator was the same for both sources. Therefore, all quantities in the spectral radiance were treated equally for the two sources in the dark room comparison.

Several subtle errors that are possible in comparison of light

sources were also avoided in this experiment. A monochromator can have preference for certain states of linear polarization of incident light, so it was verified that both sources emitted unpolarized light. Atmospheric water vapor could attenuate blue light, but in this method the two sources would have been affected equally and the ratio determined would not be changed. Lens aberrations could allow light to enter the monochromator from a region of the emitter not intended for acceptance by the entrance slit; therefore the dimensions of the sources were made identical so that the effect would be the same in each case. The calibration of the primary standard was said to apply only to light in a $2\frac{1}{2}^\circ$ cone, so the imaging lens was arranged to subtend a smaller cone. This lens was also sufficiently far from the monochromator to ensure that it did not over-fill the monochromator optics. The photomultiplier aperture was kept well inside the cone emitted from the monochromator exit slit so that the photomultiplier cathode was uniformly illuminated. It thus received light in a uniform portion of the cone where small variations in position would have negligible effect. Finally, the sources were well suited for comparison since their spectra differed by no more than a factor of three over the spectral range of interest. An undesired 0.3 percent transmission of light of all wavelengths through the monochromator by internal scattering was shown to have negligible effect on the comparison. This conclusion was reached in examination of the spectra of the standards and the photomultiplier spectral quantum efficiency, which indicated that any spurious signal produced in the photomultiplier by this scattered light would be small compared to the true signal produced by photons of the desired wavelength.

The spectral radiances of the two sources were compared at 60 different wavelengths from 3500 Å to 5300 Å, with primary attention focused on the wavelengths in the passbands of the two interference filters. This spectral range was scanned three different times over a period of two days. These three determinations of the absolute spectral radiance of the secondary standard agreed within 10 percent with no systematic variation observed among the three sets of data.

Absolute Spectral Transmittances of Interference Filters

The spectral transmittance of each of the two interference filters was determined in the dark room calibration facility in Figure 21, with the secondary standard as the light source. The transmittance of a filter was determined for the wavelength selected at the monochromator by taking the ratio of the signal observed with the filter in the beam to that observed without the filter. In each of these two measurements background noise was assessed by observing the count rate with the opaque surface blocking only the beam entering the monochromator from the lens. This noise was subtracted from the associated observed count rate in the calculation of the transmittance.

The transmittance of each filter was determined in this manner at 35 different wavelengths. Each of the two spectral transmittances was measured three times over a period of three days. The three determinations of each transmittance differed no more than five percent, and no systematic variation was found among the three sets of data.

Transference of Calibration to Optical Detection System

The final step in calibration of the optical detection system

involved the placement of the secondary standard of spectral radiance at a known position in the collision volume and observation of the detection system response to the emission with each interference filter in the optical path. Background noise was assessed by observing the count rate with the secondary standard turned off. The count rate attributed to the secondary standard was the difference between the total count rate observed and the noise count rate.

Since the secondary standard was found to radiate isotropically at least over the solid angle subtended by the photon detection system, this source simulated for the detection system a plane of isotropic photon radiators. The relative calibration of the detector response determined the dependence upon the position of an isotropic photon radiator. The absolute level of this relative photon detection efficiency could be deduced from the response to a plane of known isotropic photon radiators, which was simulated by the secondary standard. The method of calculation is presented in detail in Appendix II.

A neutral density filter was used over the secondary standard while it was in the collision volume to reduce the emission so the detector could be operated in the counting mode. The filter absolute transmittance was determined by Epply Laboratories. The count rate was further reduced by a known factor in either of two ways: reducing the voltage on the secondary standard or introducing another calibrated attenuator into the optical path. These methods were found to give results that differed by no more than four percent.

Response of the detection system with the 4554 Å filter in the

optical path to the secondary standard was ascertained with the secondary standard voltage reduced. The corresponding reduction in detector response was determined by introducing an extra attenuator to keep the count rate within the operating range while comparing eight observations at full voltage (with a deviation of 0.3 percent from the mean) to nine observations at the reduced voltage (with a deviation of one percent from the mean). At the reduced voltage the detector response was observed at four different times over a period of three hours without the extra attenuator, and the results deviated only 0.2 percent from the mean. The detector response to the secondary standard with full voltage applied was then taken to be the response at reduced voltage, multiplied by the factor by which emission had been reduced in diminishing the voltage.

The response of the detection system with the 4934 Å filter in the optical path to the secondary standard was obtained with a calibrated attenuator introduced into the optical path to keep the count rate in the operating range. This attenuator was calibrated on two different days by observing its effect on a light beam under observation by the detection system using the 4934 Å filter; these calibrations differed by less than one percent. Five determinations of the response of the optical system with the 4934 Å filter to the secondary standard were made over a period of one day, and these deviated from the mean only 0.2 percent.

To maintain the absolute calibration of the detection system completed in the above observations, the detection system response was also taken at that time to a radioactively excited phosphor source

inserted in a well defined position in the optical path just outside the chamber window. Since such a source had been found to be quite stable, it was used regularly to check for changes in detection system sensitivity during all subsequent operation of the experiment.

The calibration of the primary standard was checked at the end of the absolute calibration phase by comparing its calibration with that of an optical pyrometer that had been recently calibrated by the manufacturer, Pyrometer Instrument Company. The radiance of the primary standard lamp at the wavelength viewed by the pyrometer was calculated to be that of a blackbody at 1922°K . An operator skilled in the use of the pyrometer obtained eight readings of the temperature of the primary standard with the pyrometer that ranged from 1923°K to 1933°K with a mean of 1927°K . This result indicated that the radiance of the primary standard had not changed appreciably since the time it was calibrated.

The method of calculation of the absolute photon detection efficiency is presented in Appendix II. There the two responses of the detection system using the two interference filters to the secondary standard are expressed in terms of the absolute spectral transmittances of the two filters, the relative calibration results, the absolute spectral radiance of the secondary standard, and the undetermined factor needed to make the photon detection efficiency absolute. These two expressions involve integration over the spectrum of the secondary standard weighted by the relative spectral response of the detection system, and integration over the dimensions of the secondary standard weighted by the relative spatial sensitivity of the detection system. Equating these expres-

sions to the two experimentally determined values of the quantities they represent creates two linear equations in the two undetermined constants of the photon detection efficiency. With these two constants determined, the absolute photon detection efficiency at each resonance wavelength is obtained by evaluating at that wavelength the absolute photon detection efficiency expression containing the transmittance of the appropriate filter.

The absolute calibration results indicate that the absolute photon detection efficiency is related to the relative values in Table 2 by the factors 1.14×10^{-4} and 1.18×10^{-4} for the wavelengths 4554 Å and 4934 Å, respectively.

The experimental uncertainties associated with the absolute optical calibration of the detection system are presented in Table 3. The many small experimental uncertainties in Table 3 are combined by simple addition to give a conservative value of ± 51 percent for the uncertainty. However, treating the constituent uncertainties as independent and taking as their combination the square root of the sum of the squares indicates an overall uncertainty of 17.3 percent.

Cross Section Measurements

The absolute emission cross sections in terms of the experimental parameters are given by Equations 3 and 4. For the electron and ion velocities used, those equations can be rewritten as

Table 3. Experimental Uncertainties Associated
with Absolute Optical Calibration

Source of Uncertainty	Associated Uncertainty in Calibration Result (%)
Relative Calibration Measurements	± 5
Calibration of Primary Standard of Spectral Radiance	± 5
Electrical Input to Primary Standard	± 3
Comparison Measurement of Secondary Standard Spectral Radiance Against Primary Standard	± 7
Electrical Input to Secondary Standard	± 5
Measurement of Interference Filter Absolute Transmittances	± 3
Use of Stable Source to Maintain Calibration	± 5
Replacing Spatial Variation by a Representative Average	± 4
Transference of Absolute Calibration to Detection System by Means of Secondary Standard	± 10
Numerical Integration on Digital Computer	± 4
Combination by Simple Addition:	± 51 percent
Combination of Square Root of Sum of Squares:	± 17 percent

$$\sigma_{4554} = \frac{S \frac{e^2 V_i V_e}{\sqrt{V_i^2 + V_e^2}} F(1-\frac{1}{3}P)}{I_i I_e D_{4554}} \approx \frac{S_e^2 V_i F(1-\frac{1}{3}P)}{I_i I_e D_{4554}} \quad (7)$$

$$\sigma_{4934} = \frac{S \frac{e^2 V_i V_e}{\sqrt{V_i^2 + V_e^2}} F(1-\frac{1}{3}P)}{I_i I_e D_{4934}} \approx \frac{S_e^2 V_i F(1-\frac{1}{3}P)}{I_i I_e D_{4934}} \quad (8)$$

where S is the detected photon rate, e is the electronic charge, V_i and V_e are the respective velocities of ions and electrons, I_i and I_e are the respective currents of ions and electrons, P is the measured polarization fraction, F is the form factor describing beam overlap, and D_{4554} and D_{4934} are the absolute photon detection efficiencies with the 4554 Å and 4934 Å filters, respectively, in the optical path.

The first step in measuring cross sections was to choose beam energies and currents. The voltages in the electron gun were set to provide maximum electron current consistent with acceptable beam blow-up. Blow-up was assessed through measurement of the current falling on the aperture plate surrounding the circumference of the electron cup entrance. The electron beam regulator was then switched on and adjusted to maintain the desired electron current. The beam was intentionally disturbed to check that the regulator would function properly. The scalers were then started at a recorded time. A complete record was kept of each voltage and current in the experiment, as well as the indicated pressure, pulsing frequency, optical filter, linear polarizer, settings on the linear pulse amplifier-pulse height analyzer, and the use of the beam regulators. A

sample data sheet is presented in Appendix IV.

Counting times on the order of 24 to 36 hours were necessary to obtain a signal representative of the cross section. This necessitated operation 24 hours per day. At least once during the day the differential form factor was measured, with the beam current regulators temporarily disabled. The indicated signal should disappear within experimental scatter unless both beams are present, so each beam was regularly turned off as an experimental check. A running total of accumulated signal and noise was kept during the day as a check on the statistics of the observed signal and noise. The regulators kept the beam currents constant overnight, as was occasionally verified by chart recorder records of the currents. The apparatus was also checked by the operator approximately in the middle of the overnight period from 10 p.m. to 8 a.m. During thunderstorm activity a circuit was employed during the night to telephone the operator in the event of a power failure.

In this manner approximately 50 measurements of 10 cross sections and associated polarization fractions were made over a period of three months. Each cross section was measured several different times, with the experimental parameters in Equations 7 and 8 being intentionally changed between runs as an experimental check.

Consistency Checks

The cross sections measured for 4554 Å emission were found to be independent of intentional variations of the experimental parameters used in Equation 7. Tables 4 and 5 list all measured cross sections for 4554 Å emission according to the values of ion current and electron current used, respectively.

Table 4. Cross Sections Measured for 4554 Å Emission with Different Values of Ion Current

3 eV		4 eV		6 eV		8 eV	
$I_i (10^{-8} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$	$I_i (10^{-8} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$	$I_i (10^{-8} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$	$I_i (10^{-8} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$
2.8	51.5	3.0	38.7	2.6	26.5	1.4	10.9
3.9	30.9	3.9	39.5	4.1	24.3	4.2	16.0
4.0	73.4	4.1	40.3	4.2	24.4		
4.2	68.2	4.2	29.3	4.5	15.1		
4.4	80.6	4.5	22.9				
5.0	51.6	5.0	39.6				

Table 5. Cross Sections Measured for 4554 Å Emission with Different Values of Electron Current

3 eV		4 eV		6 eV		8 eV	
$I_e (10^{-6} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$	$I_e (10^{-6} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$	$I_e (10^{-6} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$	$I_e (10^{-6} \text{ amp})$	$\sigma (10^{-16} \text{ cm}^2)$
1.0	78.5	2.5	25.2	3.0	26.5	3.0	10.9
1.5	31.8	3.0	37.1	4.0	24.4	4.0	17.9
2.0	49.2			5.0	15.1	7.0	12.1

Table 6 presents the result for each value of the form factor that occurred, and Table 7 lists the cross sections measured with various values of the ion energy. Absence of systematic variation of the indicated cross sections with any of these experimental parameters is taken as evidence that the apparatus performed properly in these measurements. The variations in Tables 4 through 7 are within the bounds of the random scatter predicted by the statistical theory in Appendix III.

It was possible to measure the cross section for 4554 Å emission at impact energies near and below the excitation threshold, but only crude estimates of the cross section for 4934 Å emission could be made for impact energies below 8 eV. This was attributed to three differences between the measurements for the two wavelengths: (1) the cross section and signal are smaller for the 4934 Å emission; (2) the noise in the region of 4934 Å was larger than in the region of 4554 Å; and (3) the modulated light from the pulsed heating of the electron source was detected significantly at 4934 Å, but not at 4554 Å.

Evidence of the problem in measuring the 4934 Å emission is found in Tables 8 and 9, where various measured cross sections for the two wavelengths are listed with the noise present during the respective measurements. Considerable correlation of the 4934 Å cross sections with background noise is revealed in these figures, while the background noise had no effect upon the 4554 Å cross sections determined. The checks performed during data taking also showed that the indicated signal at 4554 Å disappeared when either beam was turned off, but the apparent 4934 Å signal with either beam turned off was on the order of one-third the indicated emission with both beams on.

Table 6. Cross Sections for 4554 Å Emission Measured with Different Values of the Form Factor

F(cm)	3 eV		4 eV		6 eV		8 eV	
	F(cm)	$\sigma(10^{-16} \text{ cm}^2)$	F(cm)	$\sigma(10^{-16} \text{ cm}^2)$	F(cm)	$\sigma(10^{-16} \text{ cm}^2)$	F(cm)	$\sigma(10^{-16} \text{ cm}^2)$
.807		30.0	.812	29.3	.830	24.4	.744	17.9
.816		37.3	.820	39.5	.833	24.3	.751	12.1
.834		80.6	.847	22.9	.850	15.1	.971	10.9
.873		73.4	.860	40.3	.897	26.5		
.901		51.6	.880	39.6				
.916		68.2	.968	38.7				
.969		51.5						

Table 7. Cross Sections for 4554 Å Emission Measured with Different Ion Energies

E(eV)	3 eV		4 eV		6 eV		8 eV	
	E(eV)	$\sigma(10^{-16} \text{ cm}^2)$	E(eV)	$\sigma(10^{-16} \text{ cm}^2)$	E(eV)	$\sigma(10^{-16} \text{ cm}^2)$	E(eV)	$\sigma(10^{-16} \text{ cm}^2)$
1000		51.6	1000	39.6	800	26.5	1000	17.9
1100		54.3	1100	33.3	1100	20.2	1100	12.1
1300		51.5	1300	38.7			1300	10.9

Table 8. Cross Sections for 4554 Å Emission Measured with Different Noise Rates Present

3 eV		4 eV		6 eV		8 eV	
noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$	noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$	noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$	noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$
183	80.6	343	29.3	195	24.4	321	10.9
215	30.0	357	22.9	302	24.3	435	12.1
248	68.2	404	38.7	341	26.5		
441	37.3	442	39.5	377	15.1		
536	51.5	502	40.3				

Table 9. Cross Sections for 4934 Å Emission Measured with Different Noise Rates Present

3 eV		4 eV		6 eV		8 eV	
noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$	noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$	noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$	noise (sec ⁻¹)	$\sigma(10^{-16} \text{ cm}^2)$
242	55.1	226	16.7	465	18.9	444	10.2
343	51.3	500	23.4	677	28.0	757	15.1
607	98.9	531	66.9	884	31.6	1772	18.3
654	145.9	631	35.1				

The counting system was checked regularly by counting the pulses from the photomultiplier with it shut off from the collision volume by the filter slide. The difference in counts registered by the two scalers in these tests varied randomly about zero and could be explained by the statistics of the noise random process treated in Appendix III. Also, in the middle of the data-taking period, a five day check of this type found that neither scaler led the other systematically. At the end of this five day period the counts accumulated in the two scalers differed by 1.6 parts in 10^4 . The random variable representing this difference in noise counts had a Gaussian distribution with a mean of zero and a standard deviation 1.5 times as large as the observed difference. Therefore, the counting circuitry was found to perform properly.

A likely cause of difficulty in measuring the 4934 Å emission, in addition to the low signal-to-noise ratio, was that the flicker of the pulsed electron filament was detected at this longer wavelength sufficiently to affect differently the number of photons detected by the two scalers. The modulation scheme given in Chapter III was chosen to minimize this effect. This flicker was definitely established to be a problem in this experiment with the other possible modulation schemes. This trouble could not be avoided by reducing the filament temperature because it was already at the minimum value that would provide sufficient beam current. The modulation rate could not be increased sufficiently to eliminate flicker altogether, because of the limited speed of response of the beams. The detection system was shielded from the electron filament light as much as possible.

Another possible cause of difficulty in measuring the 4934 Å emission was that the dead times of the two counting channels were different. Although the checks at moderate count rates indicated that neither scaler led the other systematically, the faster count rate caused by the greater noise at the longer 4934 Å wavelength could have been counted differently in the two channels. At a pulse rate much higher than that normally encountered in the cross section measurements, the signal-plus-noise channel was found to lead the noise channel on the order of one part in one hundred. It was therefore possible at the noise rates encountered in the measurement of 4934 Å emission that a difference in the dead times of the two channels could have caused the signal-plus-noise scaler to lead the other by an amount on the order of one part in 10^4 . This would have caused the cross section to appear too large, as was the case. Reducing the gain in an attempt to avoid the error from such dead time problems did cause the measured 4934 Å cross section to approach the expected value, but the results were deemed unsatisfactory for energies below 8 eV.

Measured Absolute Cross Sections

The absolute cross sections determined are presented in this section, along with a discussion of the associated experimental uncertainties.

The polarization fractions of 4554 Å emission measured at various energies are presented in Table 10, where it is seen that polarization has significant effect near threshold. From limited polarization measurements above 8 eV Bacon³ estimated that the polarization fraction from 8 to 98 eV was less than 0.15, so he added ± 5 percent to the uncertainty

in his relative cross section values instead of including polarization explicitly. In the present experiment less emphasis was placed on measuring the polarization fraction than on determination of the signal S , since the former was weighted by the factor $\frac{1}{3}$ in the cross section formulas. Each value of P in Table 10 represents the average of two determinations made on separate days, and each uncertainty represents the greater deviation from the mean of these two results.

Table 10. Polarization Fractions Measured for 4554 Å Emission at Impact Energies Near the Excitation Threshold

Impact Energy (eV)	Measured Polarization Fraction*
3	+0.68 ± 0.15
4	+0.52 ± 0.30
6	+0.67 ± 0.20
8	-0.099 ± 0.20

*The uncertainty represents the greater deviation from the mean of two determinations.

The absolute emission cross sections for the $6^2P_{3/2}^o \rightarrow 6^2S_{1/2}$ transition, in which 4554 Å photons are produced, are given in Table 11. There the results above 8 eV are obtained by normalizing Bacon's³ relative curve of cross section versus energy to the present absolute result at the 8 eV point. The results listed in Table 11 at and below 8 eV explicitly include polarization effects, but polarization was found to be negligible at energies above 8 eV within the experimental uncertainty.

Table 11. Measured Absolute Cross Sections
for the $6^2P_{3/2}^0 \rightarrow 6^2S_{1/2}$ Transition.

Energy (eV)	σ^* (10^{-16}cm^2)	Systematic Uncertainty (%)	Random Uncertainty (%)	Uncertainty from Polarization	Total**** Uncertainty (%)
2.5	-0.66	± 10	***	***	***
3	41.2	± 10	$\pm 25^{**}$	± 6	± 41
4	28.9	± 10	$\pm 21^{**}$	± 12	± 43
6	18.3	± 10	$\pm 22^{**}$	± 9	± 41
8	15.8	± 10	$\pm 25^{**}$	± 6	± 41
18	11.6	± 6	± 10	± 5	± 21
28	9.5	± 6	± 10	± 5	± 21
38	8.2	+7, -6	± 10	± 5	+22, -21
48	7.3	+9, -6	± 10	± 5	+24, -21
58	6.7	+9, -6	± 10	± 5	+24, -21
68	5.9	+10, -6	± 10	± 5	+25, -21
78	5.5	+10, -6	± 10	± 5	+25, -21
88	5.0	+11, -6	± 10	± 5	+26, -21
98	4.5	+12, -6	± 10	± 5	+27, -21

*Values at 8 eV and below are averages of several measurements in which each measurement is weighted by its counting time.

Values above 8 eV are the relative results of Bacon³ normalized to the present absolute results at 8 eV. The uncertainties above 8 eV are quoted from Bacon and explained in the text.

**Ninety-five per cent confidence limits calculated from observed signal and noise with statistics derived in Appendix III. All but two of 23 points are inside these limits.

***The statistical theory of Appendix III is not applicable to this case because the average signal is approximately zero. It is more appropriate to represent the quality of this data by the counting time spent in measuring it, which is approximately equal to the times for the 6 eV and 8 eV points.

****Uncertainty in absolute optical calibration is not included here; it is presented in Table 3.

Conservative values of uncertainties are presented also in Table 11. The systematic uncertainties at and below 8 eV are classified as follows: three percent uncertainty in each of the parameters F , I_1 , and I_e ; and one percent uncertainty in V_1 . The systematic uncertainties above 8 eV were given by Bacon³ for his uncertainties in the foregoing four parameters together with a pressure-dependent error found at 40 eV and above. The random errors at 8 eV and below represent 95 percent confidence limits for the present results, calculated from the statistical behavior derived in Appendix III. The random errors above 8 eV were given by Bacon³ to represent his maximum experimental scatter in that they include all but three of 109 points. His assignment of ± 10 percent to the random error was conservative, since his standard deviations of data at these points were between four and seven percent, and the 90 percent confidence limits were between two and five percent. The uncertainties associated with the polarization fraction above 8 eV were obtained by Bacon³ by estimating from his data the maximum polarization that could exist at those energies. The uncertainties associated with the polarization at 8 eV and below are obtained from Table 10.

The absolute emission cross sections for the $6^2P_{1/2}^0 \rightarrow 6^2S_{1/2}$ transition, in which 4934 Å photons are emitted, are given in Table 12. These absolute values are obtained by normalizing the relative results of Bacon³ to the absolute results for 4554 Å emission, using the ratio between the two cross section curves given by Bacon.

Conservative values of experimental uncertainties are also included in Table 12. The values due to systematic, random, and polarization

Table 12. Measured Absolute Cross Sections
for the $6^2P_{1/2}^0 \rightarrow 6^2S_{1/2}$ Transition.

Energy (eV)	σ^* (10^{-16}cm^2)	Systematic Uncertainty (%)	Random Uncertainty (%)	Uncertainty from Polarization (%)	Total** Uncertainty (%)
8	8.0	± 6	± 30	± 5	± 41
18	5.9	± 6	± 20	± 5	± 31
28	4.8	± 6	± 20	± 5	± 31
38	4.1	+7, -6	± 20	± 5	+32, -31
48	3.7	+9, -6	± 20	± 5	+34, -31
58	3.4	+9, -6	± 20	± 5	+34, -31
68	3.0	+10, -6	± 16	± 5	+31, -27
78	2.8	+10, -6	± 16	± 5	+31, -27
88	2.5	+11, -6	± 16	± 5	+32, -27
98	2.3	+12, -6	± 16	± 5	+33, -27

*These values are obtained by normalizing the relative results of Bacon³ to the absolute results in Table 11. The uncertainties are quoted from Bacon and explained in the text.

**Uncertainty in absolute optical calibration is not included here; it is presented in Table 3.

fraction uncertainties were obtained by Bacon³ in the same manner as he determined those quantities in Table 11. In Table 12 the assignments of values to the random error were conservative; they range from 16 to 30 percent, but the standard deviation ranged only from 5 to 24 percent and the 90 percent confidence limits varied from 3 to 15 percent.

The absolute cross sections listed in Table 11 and Table 12 are presented graphically in Figure 22. The cross section for 4554 Å emission does go to zero at the excitation threshold, well within the experimental uncertainty. An attempt was made to resolve more detail concerning the energy dependence of the cross section for 4554 Å emission nearer the excitation threshold by measuring at 2.85 eV. The result of $34.8 \times 10^{-18} \text{ cm}^2$ is smaller than the result at 3 eV, but this could easily be due to the electron beam energy spread extending partially below the 2.7 eV excitation threshold in the measurements at 2.85 eV. Therefore, the measurements at 2.5 eV and 3 eV represent the closest unambiguous examination of behavior very near threshold that is allowed by the electron beam energy spread.

Figure 22. Experimental Absolute Emission Cross Sections

CHAPTER V

COMPARISONS WITH OTHER RESULTS

The cross sections measured in this experiment represent photon emission in downward transitions from the $6^2P_{1/2}^0$ state and the $6^2P_{3/2}^0$ state directly to the $6^2S_{1/2}$ ground state. These emission cross sections can differ from the cross sections for excitation of the $6^2P_{1/2}^0$ state or the $6^2P_{3/2}^0$ state from the $6^2S_{1/2}$ ground state due to branching or to cascading. The measured values of the branching ratios for the $6^2P \rightarrow 6^2S$ and $6^2P \rightarrow 5^2D$ transitions of 0.74 and 0.26, respectively, given by Gallagher²⁶ are used to compare excitation cross sections to the present emission cross sections. No correction is made for cascading because no $6D \rightarrow 6P$ transitions could be detected experimentally.

The only other experimental result concerning the emission cross sections near threshold is that of Hinnov, et al.³⁸ From observations of the population densities of the 6^2P , 6^2S , and 5^2D levels of the Ba^+ ion in a barium plasma, they determined the rate of excitation of the 6^2P levels. From this result they deduced that the cross section at threshold for the $6^2S_{1/2} \rightarrow 6^2P_{3/2}^0$ excitation was $46.6 \times 10^{-16} \text{ cm}^2$ and the cross section at threshold for the $6^2S_{1/2} \rightarrow 6^2P_{1/2}^0$ excitation was found to be $29.9 \times 10^{-16} \text{ cm}^2$. These two cross sections were stated to be reliable to about a factor of two, but the relative accuracy was given as 10 percent. The threshold emission cross section can be obtained from the threshold excitation cross section of Hinnov, et al.³⁸ through multiplication of the branching

ratio measured by Gallagher.²⁶ The deduced value of $34.5 \times 10^{-18} \text{ cm}^2$ is presented in Figure 23.

A Coulomb-Bethe approximation has been applied to excitation of positive ions at energies near threshold by Gailitis.¹⁹ The oscillator strength required in his excitation cross section formula is obtained from the results of Gallagher.²⁶ The resulting excitation cross sections are converted to emission cross sections through multiplication by Gallagher's²⁶ branching ratio of 0.74. This permits comparison with the present emission cross sections given in Figure 23.

Calculations of the cross sections for $6S \rightarrow 6P$ excitation in Ba^+ by electron impact with Coulomb-Born I and Coulomb-Born II approximations have been performed by Petrini.²⁰ His excitation cross sections, converted to emission cross sections through multiplication by the branching ratio of 0.74, are presented in Figure 23.

Seaton²¹ has devised a method for estimating excitation cross sections for positive ions near threshold. He replaces the gaunt factor in the Bethe approximation for neutrals by an empirical effective gaunt factor for positive ions. Conversion of his excitation cross sections to emission cross sections has been accomplished through multiplication by the branching ratio of 0.74 as in the previously discussed cases. The results are presented in Figure 23, using values of the effective gaunt factor given by van Regemorter³⁹ for positive ions and the oscillator strength measured by Gallagher.²⁶

Theoretical values of the polarization fraction are provided by Percival and Seaton,²³ who give values for polarization fractions at

Figure 23. Comparisons of the $6^2P_{3/2}^o \rightarrow 6^2S_{1/2}$ Cross Sections with Results of Others³

threshold and very high energies for the $^2P_{3/2} \rightarrow ^2S_{1/2}$ transitions in alkali metal atoms for various nuclear spin quantum numbers. Polarization at intermediate energies depends on detailed cross section information not available. Applying the barium nuclear spin quantum numbers given by Gallagher²⁶ indicates a polarization fraction for the 4554 Å emission of +53 percent at threshold and -37 percent for very large energies. These theoretical predictions agree with the present experimentally determined values of polarization within the experimental uncertainty.

CHAPTER VI

CONCLUSIONS

The crossed beam technique has been used to measure absolute emission cross sections for the excitation of electric dipole transitions in the Ba^+ ion by electron impact at energies near and below threshold. The basic experimental method involves intersecting modulated ion and electron beams at right angles in a well defined collision volume. A portion of the photon flux radiated from the collision volume by excited ions is detected by an optical system viewing the collision volume along the axis perpendicular to both beams. The total emission is calculated from the portion detected using the experimentally determined response of the detection system to isotropic radiation and a correction for anisotropy, obtained from the polarization of detected emission. The emission cross section is then calculated from the total emission, the two beam currents and their spatial distributions, and the energies.

Techniques and devices have been developed to absolutely calibrate an optical detection system operating in the counting mode as a function of the wavelength and point of origin of the photons detected. A stable point source of light has been devised to determine the variation of the detection system response with the position in the collision volume where the photons are produced. Another small light source has been developed for transferring to the detection system the calibration of a tungsten ribbon standard of spectral radiance traceable to blackbody standards.

Techniques of careful spectral comparison of the sources are used for this purpose.

An electron source has been developed with the energy resolution and current necessary for crossed beam measurements in the 3-20 eV range. The current capability is provided by direct heating of appropriate filament materials and beam focusing. The energy resolution is achieved through application of pulsed heating voltage only while no current is being withdrawn. This tool made possible the examination of the range of impact energies near and below the excitation threshold.

The only other experimental result available for comparison is in agreement well within the combined experimental uncertainty. Available theoretical calculations compare poorly with the present results, as well as with each other. This is attributed to the rather drastic approximations used in the theoretical calculations. The relative success of van Regemorter's result can be credited to use of an empirical factor based on experimental results. The calculations employing the Born approximation apparently overestimate the cross section, which is typical for that type of calculation at low energies.

APPENDIX I

DERIVATION OF THE CROSS SECTION IN TERMS OF EXPERIMENTAL PARAMETERS

The absolute emission cross section is that function of impact energy used to relate the total photon emission from Ba^+ ions excited by electron impact to the densities and relative velocity of the ions and electrons. Consider a group of Ba^+ ions with density $N_i \text{ cm}^{-3}$ moving with relative velocity V_r through a group of electrons with density $N_e \text{ cm}^{-3}$. The number of photons per second produced by collisions in a volume dV is proportional to the respective densities of ions and electrons, their relative velocity, and the size of the volume. The number of photons produced per second in volume dV can accordingly be written as

$$R \text{ sec}^{-1} = \sigma(N_i \text{ cm}^{-3})(N_e \text{ cm}^{-3})(V_r \frac{\text{cm}}{\text{sec}})(dV \text{ cm}^3) \quad (\text{A-1})$$

where σ is the constant of proportionality. Analysis of Equation A-1 shows that σ should have the dimensions of area. This parameter σ is called the cross section for emission of photons from Ba^+ ions excited by electron impact. It is a function of the energy of the electrons. The cross section can be interpreted as the effective area presented by a Ba^+ ion to electrons such that the number of electrons striking the area, calculated on a purely geometrical basis, is the same number that caused the ion to emit photons.

In this experiment the signal S is the count rate observed in the photon detection system that is attributed to partial detection of the photons emitted from excited ions. If this emission were isotropic, the contribution dS to the signal by photons of wavelength λ originating in volume element $dx dy dz$ at x, y, z would be given by

$$dS = N(x, y, z, \lambda) R \quad (A-2)$$

The absolute photon detection efficiency $N(x, y, z, \lambda)$ gives the fraction of photons of wavelength λ radiated isotropically from the point (x, y, z) that is actually registered as counts by the detection system.

If the photons are not radiated isotropically, the photon flux Φ observed at a position on the axis perpendicular to both beams is related to the average photon flux, $\bar{\Phi}$, by

$$\bar{\Phi} = (1 - \frac{1}{3}P) \Phi. \quad (A-3)$$

The polarization fraction P is defined as

$$P = \frac{\Phi_{||} - \Phi_{\perp}}{\Phi_{||} + \Phi_{\perp}} \quad (A-4)$$

where $\Phi_{||}$ and $\Phi_{\perp}$ are the fluxes of photons observed to have electric vectors polarized respectively parallel and perpendicular to the electron beam.²³ Therefore, the observed signal due to non-isotropic dipole radiation from the element $dx dy dz$ at (x, y, z) should be written as

$$dS = \frac{N(x,y,z,\lambda) R(x,y,z,\lambda)}{(1-\frac{1}{3}P)} \quad (A-5)$$

The observed signal is accordingly related to the cross section in A-1 by

$$dS = \frac{N(x,y,z,\lambda) N_i(x,y,z) N_e(x,y,z) V_r}{(1-\frac{1}{3}P)} dx dy dz \sigma. \quad (A-6)$$

The quantities N_i , N_e , and V_r are not directly measured. The ion density is related to the density of current moving along the x-axis with velocity V_i by

$$N_i = \frac{j_i(y,z)}{eV_i} \quad (A-7)$$

and the electron density is similarly given by

$$N_e = \frac{j_e(x,z)}{eV_e} \quad (A-8)$$

where j_e is the electron current density moving along the y-axis with velocity V_e . The particle velocities are calculated from their respective energies. Since the relative velocity is

$$V_r = \sqrt{V_i^2 + V_e^2} \quad (A-9)$$

the observed differential signal in A-6 can be written

$$dS = \frac{N(x,y,z,\lambda) j_i(y,z) j_e(x,z) \sqrt{V_i^2 + V_e^2}}{(1-\frac{1}{3}P) e^2 V_i V_e} dx dy dz \sigma. \quad (A-10)$$

The total signal is calculated by integrating over the entire collision volume the contributions given in Equation A-10. Since in this particular experiment the ion and electron densities are independent of y and x , respectively, and $N(x,y,z,\lambda)$ was found to be independent of z , the integral can be written

$$S = \frac{\sigma}{(1-\frac{1}{3}P)} \frac{\iint N(x,y,z,\lambda) dx dy}{e^2 V_i V_e} \frac{I_i I_e \sqrt{V_i^2 + V_e^2}}{F} \quad (A-11)$$

where

$$J_i(z) = \int_y j_i(y,z) dy \quad (A-12)$$

$$J_e(z) = \int_x j_e(x,z) dx \quad (A-13)$$

$$F = \frac{\int J_i(z) dz \int J_e(z) dz}{\int J_i(z) J_e(z) dz} \quad (A-14)$$

Therefore the cross section can be written in terms of experimental parameters as

$$\sigma = \frac{S(1-\frac{1}{3}P) e^2 V_i V_e F}{\iint_{x,y} N(x,y,\lambda) dx dy \sqrt{V_i^2 + V_e^2} I_i I_e} \quad (A-15)$$

which is equivalent to Equations 3 and 4 if the quantity $\iint_{x,y} N(x,y,\lambda) dx dy$ is replaced by D_{4554} or by D_{4934} , depending on which emission cross section is designated.

The form factor F is calculated approximately from the beam current distributions determined with the scanning slits described in Chapter III. If the beams are scanned by slits of width Δz and the differential ion and electron currents at position number k are given by i_{ik} and i_{ek} , respectively, then the form factor in Equation A-14 is approximated by summation over all values of k as

$$F \approx \frac{\sum i_{ik} \Delta z}{\sum i_{ik}} \frac{\sum i_{ek} \Delta z}{\sum i_{ek}} = \Delta z \frac{\sum i_{ik}}{\sum i_{ik}} \frac{\sum i_{ek}}{\sum i_{ek}} \quad (\text{A-16})$$

APPENDIX II

DERIVATION OF N_{4554} AND N_{4934} IN TERMS OF EXPERIMENTALLY
OBSERVED QUANTITIES

The absolute photon detection efficiency defined in Chapter II is written as

$$N(x,y,z,\lambda) = (a\lambda+b) n(x,y,z) F(\lambda). \quad (A-17)$$

The factor $F(\lambda)$ is the measured absolute transmittance of either interference filter; the relative spatial factor $n(x,y,z)$ is determined in the relative calibration phase; and the factor $(a\lambda+b)$ is to be experimentally determined in the absolute calibration procedure so that the overall product is absolute. The linear variation with wavelength is included to allow representation of a linear photomultiplier spectral response in the range 4500 Å to 4900 Å, in accord with the manufacturer's data and the published characteristics of cooled photomultiplier tubes.^{40,41} The manufacturer's data for the uncooled tube indicate the assumed linear spectral variation, and the published data on the effects of cooling show that this characteristic is unchanged. It will now be shown how the unknown constants a and b can be calculated from knowledge of $n(x,y,z)$, $F(\lambda)$ for the appropriate filter, and measurements made with the secondary absolute standard of spectral radiance in the collision volume of the crossed beam apparatus.

The secondary standard of spectral radiance described in Chapter III

is placed at a precisely known position in the collision volume and observed by the detection system with each of the two filters, yielding respective count rates designated as C_{4554} and C_{4934} . Let $W(\lambda) \times \frac{\text{photons/sec}}{(\text{mm})^2 (\text{\AA})(\text{steradian})}$ be the absolute spectral radiance of the secondary standard that was obtained by direct comparison with the primary standard of absolute spectral radiance. It was found experimentally that the emission of the secondary standard is isotropic over the solid angle subtended by the detection system. This secondary standard then simulates for the detection system a plane, from each point of which there must be a total of $4\pi W(\lambda) \frac{\text{photons/sec}}{(\text{mm})^2 \text{\AA}}$ radiated isotropically in all directions (i.e., the secondary standard simulates, as far as the detection system is concerned, the situation where 1mm^2 radiates isotropically a total in all directions of $4\pi W(\lambda)$ photons/sec with wavelengths in an interval one Angstrom wide, centered at wavelength λ).

The count rates C_{4554} and C_{4934} can be calculated as

$$C_{4554} = \int_x \int_y \int_\lambda N_{4554}(x, y, z_0, \lambda) 4\pi W(\lambda) dx dy d\lambda \quad (\text{A-18})$$

$$C_{4934} = \int_x \int_y \int_\lambda N_{4934}(x, y, z_0, \lambda) 4\pi W(\lambda) dx dy d\lambda \quad (\text{A-19})$$

where N relates total photons produced to counts registered, and the integration extends over the two spatial dimensions and the spectrum of the secondary standard, which is in the plane $z = z_0$. Substituting the individual factors for $N(\lambda)$ gives

$$C_{4554} = \int_x \int_y \int_{\lambda} (a\lambda+b) n(x,y,z_0) F_{4554}(\lambda) 4\pi W(\lambda) dx dy d\lambda \quad (A-20)$$

$$C_{4934} = \int_x \int_y \int_{\lambda} (a\lambda+b) n(x,y,z_0) F_{4934}(\lambda) 4\pi W(\lambda) dx dy d\lambda \quad (A-21)$$

The determination of N_{4554} and N_{4934} is completed by use of the measured values of C_{4554} and C_{4934} to solve the above equations for a and b . This can be seen clearly by rewriting Equations A-20 and A-21 as

$$C_{4554} = [aI_1 + bI_2] I_5 \quad (A-22)$$

$$C_{4934} = [aI_3 + bI_4] I_5 \quad (A-23)$$

where

$$I_1 = \int_{\lambda} \lambda F_{4554}(\lambda) 4\pi W(\lambda) d\lambda \quad (A-24)$$

$$I_2 = \int_{\lambda} F_{4554}(\lambda) 4\pi W(\lambda) d\lambda \quad (A-25)$$

$$I_3 = \int_{\lambda} \lambda F_{4934}(\lambda) 4\pi W(\lambda) d\lambda \quad (A-26)$$

$$I_4 = \int_{\lambda} F_{4934}(\lambda) 4\pi W(\lambda) d\lambda \quad (A-27)$$

$$I_5 = \int_x \int_y n(x,y,z_0) dx dy \quad (A-28)$$

These integrals are performed on a digital computer. Finally, the absolute photon detection efficiency is written as

$$N_{4554}(x,y,z,\lambda) = (a\lambda+b) n(x,y,z) F_{4554}(\lambda) \quad (A-29)$$

$$N_{4934}(x,y,z,\lambda) = (a\lambda+b) n(x,y,z) F_{4934}(\lambda) \quad (A-30)$$

using the values of a and b obtained by solving Equations A-22 and A-23.

APPENDIX III

STATISTICS OF THE SIGNAL DETECTION PROBLEM

The elements of the signal processing are diagrammed in Figure 24. The switch divides the noise, which has an average rate $N \text{ sec}^{-1}$, into two independent samples, N_1 and N_2 . Each sample therefore has an average rate of $\frac{1}{2}N \text{ sec}^{-1}$. The switch sends all the true signal, which has an average rate $S \text{ sec}^{-1}$, into scaler 1 only. If the outcome of counting for T seconds is that $N_1 = N_2$, the true signal has been perfectly measured. In the usual case where $N_1 \neq N_2$, the measurement indicates a signal of $ST + (N_1 - N_2)$. The error $(N_1 - N_2)$ is thus defined as the false signal, F .

Statistical Model for Pulses

The arrivals of signal pulses and of noise pulses are modeled as Poisson processes, as is common practice.^{42,43} The properties of such a process are the following: (1) the pulses tend to arrive with some average rate over long periods; (2) the time of occurrence of each pulse is independent of the times of occurrence for all others; and (3) the number of pulses in one time interval is independent of the numbers in other time intervals. It can be shown⁴⁴ that these properties lead to the distribution

$$P_{AT}(k) = \frac{(AT)^k e^{-AT}}{k!} \quad (\text{A-31})$$

S = TRUE SIGNAL

N = NOISE

N_1 = THAT HALF OF THE NOISE SWITCHED TO SCALER #1

N_2 = THAT HALF OF THE NOISE SWITCHED TO SCALER #2

Figure 24. Flow Graph of Signal and Noise Components

where P is the probability of k pulses occurring in T seconds if the average rate is A pulses per second.

A more heuristic approach is to imagine the construction of a member of the ensemble of all possible pulse trains having the above three properties. First, one arranges a pulse train with AT' pulses placed at independent times chosen completely at random from the time interval $(0, T')$. The pulse train thus constructed has properties (1) and (2) above, and the probability of finding k pulses in T seconds where $T < T'$ is given by the binomial distribution

$$P_{AT}(k) = \frac{(AT')!}{(AT'-k)! k!} \left(\frac{T}{T'}\right)^k \left(1 - \frac{T}{T'}\right)^{AT'-k} \quad (A-32)$$

This pulse train lacks property (3) above, because the location of $(AT'-1)$ pulses in a time interval determines that there must be exactly one pulse in the remainder of the time T' . To make all time intervals independent, let $T' \rightarrow \infty$. Taking this limit in Equation A-32 gives⁴⁵

$$P_{AT}(k) = \frac{(AT)^k e^{-AT}}{k!} \quad (A-33)$$

which is the Poisson distribution given in Equation A-31.

The first and second moments of the Poisson distribution are respectively AT and $(AT)^2 + AT$.⁴⁶ Therefore, the variance of this distribution is AT and the standard deviation is $\sqrt{AT}$.

Statistics of False Signal

The false signal is defined as that random variable specifying the difference between the noises N_1 and N_2 that are counted in time T by scalers 1 and 2, respectively. Since these noises result from counting Poisson processes each having average rate $N/2$, both N_1 and N_2 have a mean of $\frac{1}{2}NT$ and a variance of $\frac{1}{2}NT$. The false signal is the difference of these two independent random variables, so it has a mean of zero and a variance of NT .

Comparison of True Signal and False Signal

When the difference is taken in counts registered in time T by the two scalers, the result is the sum of these independent variables: true signal and false signal. The registered signal thus has a mean that is the sum of the means of the component signals, or just ST . The variance of the registered signal is $(ST+NT)$, which for this experiment can be considered NT because $N \gg S$.

To ensure that the registered signal is representative of its mean ST , the standard deviation $\sqrt{NT}$ should be small compared to the mean. These two parameters are therefore compared in this experiment by a quality factor defined by

$$Q = \frac{ST}{\sqrt{NT}} = \frac{S \sqrt{T}}{\sqrt{N}} = \sqrt{\frac{S}{N}} \sqrt{ST} \quad (\text{A-34})$$

Further Interpretation of Quality Factor

A further interpretation of the quality of data is revealed by the graph in Figure 25. The Poisson distribution of the false signal is

Figure 25. Statistical Interpretation of Data in Terms of Q Factor

well approximated by a Gaussian distribution with the same mean and variance if $NT > 100$,⁴⁵ which condition is certainly satisfied by the parameters used in this experiment. The probability that $|\text{false signal}| \leq \frac{1}{V} \text{ (ST)}$ can be calculated from the Gaussian distribution of false signal for given values of Q and V . For example, if $Q = 10$, the probability is approximately 0.95 that the magnitude of the false signal is less than 0.2 ST. Therefore, Figure 25 gives a detailed probabilistic comparison of false signal and true signal in a body of data which has a known value of Q . It should be remembered that the error treated in this appendix as false signal is associated with only the theoretical statistics of the pulses counted, and it does not include any uncertainties that may be associated with the experimental apparatus.

APPENDIX IV

TYPICAL EXPERIMENTAL PARAMETERS AND DATA

Typical experimental parameters and data are presented in Tables 13, 14, and 15. The first two of these tables represent the two sides of a data sheet used in the procurement of data. The last table represents the sheet used to record beam profiles.

Table 13 shows the front side of a typical data sheet, which contains the counting data and other parameters needed to calculate the cross sections. Scaler #1 counted signal plus noise, while scaler #2 counted only noise.

All observable experimental parameters not explicitly appearing in the cross section formulas were recorded, either on the front side or the back side of the data sheet. The back side of a typical data sheet is shown in Table 14.

A new data sheet was begun whenever any values of experimental parameters changed. The combination of all counting periods recorded on a single data sheet constituted one measurement of a cross section. This measurement was segmented into the several periods on the sheet as a running check of the statistics of the observed signal and noise. Measurements of the same cross section made in this manner at various times were averaged with each value weighted by the counting time spent in measuring it.

A typical beam profile data sheet is presented in Table 15. The calculation of the form factor with these data is carried out on this sheet.

TABLE 13. SAMPLE DATA SHEET, FRONT SIDE

TIME COVERED 2200 June 7 - 0905 June 8ELECTRON VOLTS 3.0ION VOLTS 1100ELECTRON MICROAMPS 1.0ION AMPS 4.2×10^{-8} APERTURE MICROAMPS 0.1POLARIZER OUT ✓WAVELENGTH IN Å 4554POLARIZER || TO ELECTRONSPOLARIZER ⊥ TO ELECTRONSFORM FACTOR IN CM. .916PRESSURE IN TORR 1.1×10^{-7}

START TIME	END TIME	SCALER 1	SCALER 2	SIGNAL COUNTS
2221	0239	1,935,421	1,932,699	2722
0249	0804	2,367,641	2,361,230	6411
0805	0835	206,057	205,894	163
0835	0905	196,974	196,574	400

TOTAL SIGNAL = 9696

TOTAL SECONDS = 37,980

AVE. SIGNAL = .255

TABLE 14. SAMPLE DATA SHEET, BACK SIDE

APPARATUS STATES FOR DATA ON REVERSE SIDE

FINE GAIN .7
COARSE GAIN 1/8
WINDOW 10
THRESHOLD 0

BASIC PULSE RATE
IN HERTZ 200

PHOTOMULTIPLIER
VOLTS 1500

COOLER AMPS 6.0

HEATER AMPS 0

ION SOURCE FIL. AMPS 18.0

ION SOURCE OVEN AMPS 7.8

REGULATOR SUPPLY VOLTS 10

EXTRACTION VOLTS 45

E. SOURCE PLATE 1 VOLTS 3

E. SOURCE PLATE 2 VOLTS 0.44

E. SOURCE PLATE 3,4 VOLTS 2.2

ION VERTICAL VOLTS 0

ION HORIZONTAL VOLTS 71

ELECTRON FILAMENT AMPS 3.3

ELECTRON CURRENT REGULATOR ON ✓
OFF

TABLE 15. SAMPLE FORM FACTOR SHEET

	initial	final
li	4.2×10^{-8}	4.2×10^{-8}
le	1.0×10^{-6}	1.0×10^{-6}

DATE June 8, 1970

TIME 0240 hours

ENERGY 3 eV

FORM FACTOR

MICRO	Δle	Δli	$\Delta le \Delta li$
1120	0×10^{-6}	0×10^{-9}	0×10^{-15}
1140	0	0	0
1160	0	.17	0
1180	0	.40	0
1200	0	.90	0
1220	.004	1.27	.005
1240	.006	1.50	.009
1260	.029	1.36	.039
1280	.039	1.26	.049
1300	.045	1.40	.063
1320	.058	1.84	.107
1340	.072	1.94	.140
1360	.088	2.25	.198
1380	.090	2.05	.184
1400	.084	2.38	.200
1420	.073	2.00	.146
1440	.068	2.25	.153
1460	.047	2.74	.129
1480	.032	3.50	.112
1500	.025	3.50	.087
1520	.010	3.10	.031
1540	.003	2.45	.007
1560	0	.44	0
1580	0	0	
1600	0	0	
1620	0	0	
1640	0	0	
	$.773 \times 10^{-6}$	38.70×10^{-9}	1.659×10^{-15}
	$\Sigma \Delta le$	$\Sigma \Delta li$	$\Sigma \Delta le \Delta li$

$$F = \frac{(0.0508) (\Sigma \Delta le) (\Sigma \Delta li)}{\Sigma \Delta le \Delta li} = \frac{(0.0508) (.773) (38.7)}{(1.659)} = 0.916 \text{ CM}$$

 $\Sigma \Delta le \Delta li$

(1.659)

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^{*} Abbreviations used herein conform to those found in the American Institute of Physics Style Manual (1963).

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VITA

Marshall Osteen Pace was born in Greenville, South Carolina on September 10, 1941. He is the son of Samuel and Margaret Osteen Pace. On April 19, 1968 he was married to Phyllis Ann Cooper.

Mr. Pace attended public schools in Columbia, South Carolina, where he was graduated from Eau Claire High School in 1959. He received the degree of Bachelor of Science in electrical engineering (Magna Cum Laude) from the University of South Carolina in 1963.

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