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An Absolute Measurement of the
Photoionization Cross Section for
Ground State Cesium Atoms

by

Thomas Bratton Cook, III

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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PREFACE

The importance of the alkali metals in a variety of laboratory and astrophysical processes has stimulated many investigations of their properties. In some cases, however, the results of theory and experiment do not agree. This is the situation in the work concerning photoionization of atomic cesium, where a survey of the literature shows a factor of two disagreement between theory and experiment in the magnitude of the cross section. This thesis reports a new measurement of the cross section for this process and resolves the earlier discrepancy between theory and experiment.

The thesis is organized as follows: Chapter I contains an introduction to the problem, a discussion of the physics of the process, and a review of both theoretical and experimental work performed prior to the present measurement. Chapter II deals with the design of the apparatus used in this study and a description of the major components. Next, a description of the experiment itself is given, including the details of measuring the quantities necessary to determine the cross section, as well as the systematic checks performed to ensure that the apparatus was operating correctly. Chapter III contains the results

of this experiment and a comparison with theoretical calculations and with previous experimental results. Options for future experiments are also discussed. Following Chapter III are several appendices containing information on some of the more technical aspects of the apparatus and measurement.

TABLE OF CONTENTS

CHAPTER I

A. Introduction	1
B. Physics of Cesium and the Other Alkalis	3
C. Previous Calculations	13
D. Previous Experiments	19

CHAPTER II

A. The Apparatus	27
(1) General	27
(2) Vacuum System	27
(3) The Oven	29
(4) The Alkali Beamline	31
(5) The Interchamber Valve	32
(6) The Beam Defining Apertures	32
(7) The Ion Collector Assembly and Detector	33
(8) The Alkali Beam Scanner and Collector	35
(9) The Laser	37
B. The Measurement	39
(1) The Photoion Signal	40
(2) The Multiplier Calibration	44
(3) The Alkali Beam Density	49
(4) The Photon Flux	53
(5) Path Length	55

CHAPTER III

A. Results and Sources of Error	56
B. Discussion of Results and Comparison with Previous Work	58
C. The Future	60
REFERENCES	63

APPENDICES

A. Manufacturers	66
B. Oven Controller	68
C. System Geometry	70
D. Biasing of the Beam Scanner	76
E. Thermopile Calibration Factor	78

CHAPTER I

A. Introduction

This thesis deals with a measurement of the photo-ionization cross section for ground state atomic cesium, a process which is formally written as

where standard notation $(n\ell^{2S+1}L_J)$ is used to describe the atomic states. Although the process is interesting in its own right, the primary motivation for this work is to verify theoretical calculations that have been recently reported, and to resolve a discrepancy between those calculations and previous experimental work. At first glance it may appear that cesium calculations might not be too difficult since cesium has one valence electron outside a closed shell of core electrons. In a simple picture, the core electrons shield the nucleus from the valence electron, leaving a net nuclear charge of one which interacts with the valence electron. To the extent that the core electrons succeed at this shielding but are otherwise inert, the term structure of the atom is hydrogenic and as such is a good candidate for theoretical treatment. Unfortunately the similarity between

the heavier alkalis and hydrogen is one of form only not of detail owing to strong spin orbit and core polarization effects that perturb the states of the heavier metals.

In order to account for these additional interactions theorists have used a conceptually simple yet quite powerful technique in treating the problem. The method, which will be described at greater length later in this chapter, involves the use of a semi-empirical model potential to approximate the field due to the core electron distribution. Two such calculations have been recently reported: One by Jon C. Weisheit¹ of Lawrence Livermore Laboratory and the other by David W. Norcross² of the Joint Institute for Laboratory Astrophysics.

Figure I-1 summarizes the previous work done on the photoionization of cesium. The theoretical calculations of Weisheit¹ (short dashes) and of Norcross² (long-short dashes) are shown as well as the most recent measurements of the process reported by G. V. Marr and C. M. Creek³ (solid line). Older measurements, from as early as the 1920's are available, but are not shown here for the sake of clarity, although they will be discussed in Section D of this chapter.

The two calculations are clearly in good agreement

Figure 1-1: Summary of atomic cesium photoionization work. — experiment of Marr and Creek; — — — calculation of Weisheit; — · — · — calculations of Norcross.

with each other ($\sim 15\%$). However the disagreement between the theories and experiment is substantial, being approximately a factor of two different over the entire energy range shown. The present experiment was undertaken in an effort to resolve this discrepancy.

B. The Physics of Cesium and the Other Alkalis

In this section the results of a simple calculation are presented which qualitatively accounts for the shape of the photoionization cross section that has been seen in Fig. I-1. The simple model presented is however not completely adequate and the effects of spin orbit coupling and polarization of the core electron distribution must be included in a manner which will be discussed.

Figure I-2 shows a compilation of experimentally obtained photoionization cross sections for the alkalis as assembled by Marr and Creek.³ Notice that the results for each atom show a slowly varying structure in the cross section that is several hundred angströms wide in each case. The origin of this shape may be seen qualitatively by way of the following simple calculations.

Consider the expression for the cross section for an electric dipole transition. The cross section, σ , is proportional to the square of the appropriate matrix

Figure I-2: Compilation of experimental photoionization cross sections in the alkalis. (From Marr and Creek.) The curves have been obtained by weighted mean values of all experiments.

element⁴

$$\sigma \propto \left[\int_{\text{all space}} \psi_f \vec{D} \psi_i d^3r \right]^2 \quad \text{I-2}$$

where ψ_f and ψ_i are respectively the final and initial wavefunctions and $\vec{D}$ is the dipole operator.

In applying this standard result to the alkalis, the initial state is nearly hydrogenic, with principal quantum number for the valence electron in the ground state being n_0 (=1 for hydrogen, 2 for lithium, etc.) and the orbital angular momentum being zero -

$$\psi_i = \psi(n_0 s) \quad . \quad \text{I-3}$$

The final state is specified by ϵ , the asymptotic energy of the ejected electron, and by p , indicating an orbital angular momentum of one -

$$\psi_f = \psi(\epsilon p) \quad . \quad \text{I-4}$$

This choice of p-waves for the final state is necessitated by the $\Delta \ell = \pm 1$ selection rule.

The dipole operator in its complete form is

$$\vec{D} = e \sum_i \vec{r}_i \quad \text{I-5}$$

where e is the electron charge and $\vec{r}_i$ is the radius vector to the i^{th} electron. The sum runs over all the electrons

in the atom. In the approximation that only the valence electron takes part in the transition, equation I-5 simplifies to

$$\vec{D} = e \vec{r} \quad \text{I-6}$$

where $\vec{r}$ is the radius vector of the valence electron.

Figures I-2 through I-8 (which follow p. 7) illustrate the behavior of the dipole matrix element (the expression in brackets in equation I-2) for several different energies of the ejected electron. The radial part of the initial state ψ_i , shown in part (a) of each of the figures, is taken to be a hydrogen (2S) state. The final state ψ_f is taken to be a spherical wave, the radial part of which is shown in figure I-3b for an energy $\epsilon_1 (= k_1^2)$. Note that,

- (1) neither final nor initial states are normalized,
- (2) the angular part of the wavefunctions is ignored since the angular integration is the same for all values of energy ϵ ,
- (3) the r^2 term in the volume element (d^3r) is neglected for convenience, and
- (4) the coulomb well is disregarded in writing down the outgoing wavefunction.

In figure I-3c is drawn the value of the integrand of the matrix element, i.e., the product

$$\psi(\epsilon_1 p) \cdot r \cdot \psi(2S)$$

as a function of radius. For the chosen value of ϵ_1 , the area under the curve (in figure I-3c) is a large negative number as noted in the figure caption. This area is the value of the radial part of the matrix element of equation I-2.

Figure I-4 shows a slightly higher energy case, ϵ_2 . As the final state wave (I-4b) oscillates more quickly in r , the value of the integrand of the matrix element (I-4c) also oscillates at higher frequency. This results in the growth of the positive parts of the matrix element at the expense of the negative. In the case shown the value of the matrix element is still negative but smaller in magnitude.

Figure I-5 shows a case, ϵ_3 , for which the value of the matrix element is very near zero. This is an extreme case of what in the literature is referred to as "cancellation in the matrix element." The phenomenon is responsible for the small photoionization cross sections in general for the alkalis, and the near zero value of the cross section in the minimum seen in sodium. This will be further discussed in a moment.

Figures I-6 and I-7 are very similar, at energies ϵ_4 and ϵ_5 , but the value of the matrix element is now positive. Finally, figure I-8 shows the case at ϵ_6 wherein the

outgoing wave oscillates very quickly in r , and as a result the value of the matrix element decreases, producing the high energy tail of the cross section.

Figure I-9a and b shows the value of the radial part of the matrix element (denoted as M) and the value of its square ($M^2 \propto \sigma$) plotted for each value of ϵ used in figures I-3 - 8. When the matrix element changes sign as happens for an outgoing energy near ϵ_3 (fig.I-5), the cross section must go to zero. The form shown for the cross section in figure I-9b is similar to that determined experimentally for cesium (or for rubidium) shown in figure I-2. However, a significant difference between the forms shown in those two figures is in the magnitude of the cross section at the minimum - being zero in the calculated case and finite in the experimental case.

It was Seaton⁴ who first accounted for the finite value of the minimum in the heavier alkalis. The key to the problem may be found by consideration of the cesium term structure (figure I-10). The ground state is designated $^2S_{1/2}$ in the usual notation ($^{2S+1}L_J$). The first two excited states are $^2P_{1/2}$ ($T = 11178 \text{ cm}^{-1}$)⁵ and $^2P_{3/2}$ ($T = 11732 \text{ cm}^{-1}$). These states differ because of the relative orientations of the spin and orbital angular momentum, the $J = 1/2$ state being slightly lower in energy

Figure I-3: The matrix element calculation for energy ϵ_1 .

Figure I-4: The matrix element calculation for energy ϵ_2 .

Figure I-5: The matrix element calculation for energy ϵ_3 .

Figure I-6: The matrix element calculation for energy ϵ_4 .

Figure I-7: The matrix element calculation for energy ϵ_5 .

Figure I-8: The matrix element calculation for energy ϵ_6 .

Figure I-9: The dependence of (a) the radial matrix element M and (b) the cross section σ on the energy ϵ of the ejected electron.

Figure I-10: Partial term diagram for cesium.

than the $J = 3/2$ state.

As mentioned earlier, the electric dipole transitions from the ground s-state must terminate in a p-state. This rule holds for both photoexcitation and photoionization. In the case of photoexcitation to low lying states, the fine structure splittings are sufficiently large that the J of the final state may be selected by proper choice of the excitation wavelength. For photoionization, however, continuum p-states are used and the different J states are degenerate so that both $P_{1/2}$ and $P_{3/2}$ are in general accessible and this must be accounted for in the calculations.

Even though the energies of the $P_{1/2}$ and $P_{3/2}$ in the continuum are the same, the wavefunctions are not. In particular, while the outgoing electron is still near the nucleus, the spin orbit interaction remains effective. This means that at small r , the potential seen by an electron in a $P_{1/2}$ state is deeper than that seen by an electron in a $P_{3/2}$ state (as is the case for $6p^2 P_{1/2,3/2}$ states just mentioned). The spin orbit interaction at small r thus pulls the wavefunction in for the $J = 1/2$ state (shortens the wavelength) while pushing the wavefunction out (lengthens the wavelength) for the $J = 3/2$ state.

If these slightly different wavefunctions are used in the calculation of the matrix element, the change of sign

occurs at different electron energies for the two states. The total cross section is calculated as the weighted sum of the two partial cross sections for transitions into each J level. This is indicated in figure I-11, where the total cross section (taken for clarity to be the simple sum of the individual cross sections) maintains its broad structure, but now rather than a zero minimum, a finite value is produced.

A measure of the importance of spin orbit coupling on assorted alkalis is indicated in Table I-1. Shown for sodium, potassium, rubidium, and cesium are the results of an early calculation by Seaton⁴ giving the value of the cross section at the minimum. It can be seen that the value of σ_{MIN} increases with atomic number, analogous to the increase of spin orbit effects suggested by the familiar penetration arguments.⁶

A computational difficulty related to the amount of cancellation that occurs in calculation of the matrix element for photoionization is shown in figure I-12. Part (a) of this figure is identical to figure I-5c, showing the value of the integrand of the transition matrix element $\psi(\epsilon_3p) \cdot r \cdot \psi(2S)$ as a function of radius from the nucleus. Figure I-12b shows the integral of this quantity as a function of r, i.e., the value of

Figure I-11: The addition of the cross sections for two spin states (j and j') to give the total cross section.

Table I-1

Values of the photoionization cross section
in the minimum

atom	$\sigma_{\text{MIN}}(\text{cm}^2)$
Na	1×10^{-23}
K	3×10^{-22}
Rb	4×10^{-21}
Cs	3×10^{-20}

Figure I-12: Figure illustrating cancellation in the matrix element near the cross section minimum.

$$\int_0^r \psi(\epsilon_3 p) r' \psi(2S) dr'$$

for each r . Consider the integral as being broken down into two parts - an inner part from zero to some r_0 and an outer part from r_0 to ∞ . It can be seen that if $r_0 \approx 4a_0$, then the value of the first integral is $\sim +4$ units while the value of the second is slightly in excess of -4 units. When the sum of the two integrals is made, the result is around -0.05 units. The consequences of this cancellation are serious. First, prior to the advent of modern computers, a great deal of effort was necessary to avoid round off errors. Second, and the more important for recent calculations, the value of the cross section is very sensitive to the details of the wavefunction. Seaton,⁴ in doing the calculations of Table I-1, was aware of both problems (the year was 1951). In the first case, he was forced to recalculate the wavefunctions for the outgoing wave since the existing three place compilation that had been reported at the time was not of sufficient accuracy for the alkalis. As for the second problem, he observed in doing calculations on sodium, near threshold, that only a 1% change in either the inner or outer integral can make a 16% change in the cross section! Obviously the theorist must be very careful if accurate results are to

be obtained in the alkalis.

A further difficulty in doing calculations on cesium is also related to the cancellation problem in the matrix element: Since the cross section is so small, it is necessary to include other interactions that would be relatively unimportant if the cross section were larger. A case in point is the effect of the coulomb repulsion between the core electrons and the valence electron in the photoionization process. This repulsion induces in the core electron distribution a polarization, the effect of which may be seen as follows.

The matrix element for the photoionization process (equation I-2) represents the dipole moment for the transition between two specified states of the atom. In the general formulation (cf. equation I-5) of the matrix element, the dipole operator $\vec{D}$, is the vector sum of the individual dipoles associated with each electron. In the approximation used earlier in this chapter it was assumed that the net contribution to $\vec{D}$ from the core electrons was zero. In fact if the core electron distribution is polarized, as it is in the heavier alkalis, the dipole operator comprises two terms

$$\vec{D} = \vec{d}_v + \vec{d}_c$$

where $\vec{d}_v$ and $\vec{d}_c$ are the dipole operators due respectively to the valence electron and to the polarization of the core electrons. Since the core dipole is the result of the repulsion between the core electrons and the valence electron, $\vec{d}_c$ is antiparallel to $\vec{d}_v$. This means that the magnitude of $\vec{D}$ is reduced:

$$|\vec{D}| = |\vec{d}_v| - |\vec{d}_c| \quad \text{I-8}$$

and as a result the transition matrix element to be calculated is also reduced.

The polarizability of the electron core in cesium is very large (see Table I-2)⁷ and consequently, the effect just described is important, and accounts for a 16% reduction in the oscillator strength for the Cs(6s → 6p) resonance line⁷ and an ever increasing effect for higher principal series transitions.⁸ The effect of core polarization on the photoionization process is more complicated owing to phase shifts in the outgoing wave so that the polarization changes not only the magnitude but also the shape of the photoionization cross section curve.^{1,8}

C. Calculations

As previously noted, there have been two recent

Table 1-2
Core Polarizability

Element	Polarizability (atomic units)
Li	0.16
Na	0.98
K	5.5
Rb	12
Cs	16

calculations of the photoionization cross section for atomic cesium. Both authors, J. C. Weisheit¹ and D. W. Norcross,² use a semiempirical model potential to mimic the potential field produced by the core electrons. Typically the model potential contains one or more adjustable parameters to permit fitting of the results to known features of the atom. The following discussion, intended to illustrate the procedure used in the calculations, is based on the work of Norcross. (Note that Weisheit's methods are much the same and differ primarily in mathematical detail.)

The radial part of the wave equation for the valence electron is written in the usual form (atomic units):

$$\left(\frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} + V(r) - \epsilon_\alpha \right) R_\alpha(r) = 0 \quad \text{I-9}$$

where ϵ_α is the energy of the state specified by the quantum number(s) α , and with radial wavefunction $R_\alpha(r)$. For bound states ϵ is negative and $\alpha = (n, l, j)$ while for continuum states ϵ is positive and $\alpha = (\epsilon, l, j)$.

The potential $V(r)$ is the sum of several terms:

$$V(r) = V_c(r, C_1) + V_p(r, C_2) + V_{so}(r) \quad \text{I-10}$$

to account for the screened coulomb field (V_c), the field due to the polarization of the core electron distribution

(V_p) and the spin-orbit interaction (V_{so}). The parameters C_1 and C_2 describe respectively, the screening of the nuclear charge by the core electrons and the polarization induced in the core by the valence electron.

For given values of C_1 and C_2 , wavefunctions and eigenenergies are calculated for a number of states. The parameters are then varied to produce as accurately as possible the known energies for the selected states. Norcross uses three states for this procedure: $6s^2S_{1/2}$, $6p^2P_{1/2}$, and $6p^2P_{3/2}$.

Once the values of C_1 and C_2 have been chosen in this way, the energies for many s- and p-states are calculated. Likewise, the radial p-state wavefunctions are found for selected continuum energies.

The s- and p-bound state energies for $n = 6-9$ are compared with known term values to demonstrate that the chosen model potential does indeed yield good results for cesium.

Having determined the valence electron wavefunctions for ground and continuum states, the total atomic wavefunction is written as a product of valence and core wavefunctions, ψ_v and ψ_c respectively:

$$\Psi = \psi_v \cdot \psi_c \quad . \quad \text{I-11}$$

The core wavefunction is a sum of two parts,

$$\psi_c = N(r) [\phi(\vec{R}) + \chi(\vec{R}, \vec{r})] \quad \text{I-12}$$

where $\phi(\vec{R})$ is the unperturbed core electron wavefunction (at point $\vec{R}$) and $\chi(\vec{R}, \vec{r})$ is the perturbation at point $\vec{R}$ due to the valence electron located at $\vec{r}$. $N(r)$ is a normalization factor.

The dipole operator is of the form used in equation I-7, which is repeated here for completeness.

$$\vec{D} = \vec{d}_v + \vec{d}_c .$$

(Recall that $\vec{D}$ is the total dipole of the atom and is composed of a dipole, $\vec{d}_v$, due to the separation of the valence electron with respect to the nucleus, and one, $\vec{d}_c$, due to the polarization of the core electron distribution by the valence electron.)

The usual matrix element

$$M(\epsilon, j) = \langle \Psi_f(\epsilon, j) | \vec{D} | \Psi_i \rangle \quad \text{I-13}$$

is calculated by taking the initial state to be the 6s ground state and the final state to be a continuum p-wave of given ϵ and j .

The cross section for ionization into the appropriate j -continuum is given by

$$\sigma_j(\epsilon) \propto M(\epsilon, j)^2 \quad \text{I-14}$$

and the total cross section is

$$\sigma(\epsilon) = \frac{1}{3} \sigma_{1/2}(\epsilon) + \frac{2}{3} \sigma_{3/2}(\epsilon) \quad \text{I-15}$$

where each partial cross section is multiplied by the appropriate statistical weight. The values of $\sigma(\epsilon)$ calculated by both Norcross² and Weisheit¹ have been shown in figure I-1.

In addition to these calculations of the photoionization cross section, both Norcross² and Weisheit¹ report the results of calculations of oscillator strengths, polarizabilities, line strength ratios, and the like. Each author presents comparisons between his results and previous experimental determinations of the appropriate quantities. The details are beyond the scope of this thesis, but in general the agreement between the two is good.

Norcross estimates his calculations to be accurate to $\pm 15\%$, which is approximately the maximum difference between the two calculations (cf. figure I-1). Taken at face value, it seems unlikely that the calculations of the photoionization cross section are greatly in error.

D. Previous Experiments

Cesium has been a popular target in photoionization studies ever since the mid-1920's. All of the attempts to measure the cross section for photoionization absolutely have been performed in gas cells and may be separated into two categories. One set of experiments, as exemplified by the work of Little⁹ (1927) and Mohler and Boeckner¹⁰ (1929), utilizes the so-called "direct" method and monitors the current of photoions to determine the cross section. The second ("indirect") method measured the decrease in the intensity of light transmitted through the vapor cell as a function of cesium pressure in order to determine the cross section. Among the experiments performed by this method are those of Braddick and Ditchburn¹¹ (1933), and Marr and Creek³ (1968). In this section the experiment of Mohler and Boeckner¹⁰ will be discussed as an example of a direct measurement, and the work of Marr and Creek³ will be described to illustrate an indirect measurement.

The apparatus of Mohler and Boeckner¹⁰ is shown in figure I-13. The glass cell contains two electrodes, one a cylinder approximately 8 cm long, 3 cm diameter with 1 cm diameter holes in both ends. The other electrode, located inside the cylinder, is a plate, almost as long as the cylinder and 1 cm wide. The cell body is maintained

Figure I-13: Apparatus of Mohler and Boeckner.

at 200 °C with the vapor pressure set by a side arm containing cesium metal at a slightly lower temperature. Light from a mercury arc was filtered to remove lines except near the atomic threshold and brought to a focus inside the cell as indicated in the figure. Photoions produced by passage of light through the cesium vapor were collected on the plate electrode, and the resulting current measured. The photon flux was measured with a calibrated thermopile. Knowing the cell geometry and temperature and using tabulated vapor pressure data a value of the cross section near threshold was calculated.

In order to determine cross sections for wavelengths other than in the selected mercury arc lines near threshold, a relative measurement was performed in a separate apparatus. The detailed procedure is not of interest here, but briefly a space charge detector was used to amplify the photoion current. Owing to the inherent gain of the space charge detector ($\sim 10^5$ in this case), measureable currents were obtainable using smaller photon fluxes. This enabled a spectrometer to be used to select out various individual lines of the lamp and still have measureable currents. The relative cross section so obtained was then normalized by use of the near threshold value previously described to give the curve labeled MB in figure I-14. This figure is

Figure I-14: Atomic absorption cross section data for cesium from Marr and Creek³ (labeled MC), from Braddick and Ditchburn¹¹ (BD), and from Mohler and Boeckner¹⁰ (MB). The results shown for BD and MB have been modified to reflect the Honig¹² results for vapor pressure data.

taken from the more recent paper of Marr and Creek³ and has been renormalized from that given in the original paper to account for more recent determinations of the cesium vapor pressure¹² than were available in the 1920's.¹³ Critical discussion of these results will be deferred until the other class of experiments shown in the figure, represented by Braddick and Ditchburn¹¹ (labeled BD) and by Marr and Creek³ (labeled MC), are discussed.

Prior to the present work the most recent measurement of photoionization in cesium is that of Marr and Creek³ reported in 1968. This experiment which is typical of the indirect measurements (i.e., measuring light absorption) is perhaps the best of its type in cesium although in the light alkalis the work of Hudson¹⁴ and Hudson and Carter^{15,16,17} is in several ways more sophisticated.

The apparatus used by Marr and Creek is shown in figure I-15, and comprises three chambers separated by lithium fluoride windows: (1) a discharge lamp source, (2) a long absorption tube, and (3) a vacuum spectrograph. Cesium metal is contained in the two indicated reservoirs. Helium, at a pressure of slightly higher than the vapor pressure of cesium at the working temperature, T , of the system, is used as a buffer gas. This slows the diffusion of the metal vapor into the cooler parts of the tube, which

Figure I-15: Apparatus of Marr and Creek.

are located beyond the constrictions.

In operation, the temperature of the cell is raised to temperatures ranging from 295 °C to 350 °C and maintained to $\pm 1/2$ °C by three sets of heaters. Light from the discharge lamp passes through the vapor cell, into the spectrometer and exposes a photographic plate. By taking comparison spectra with the cell alternately hot and cold, the ratio of the transmitted intensity with cesium vapor and without cesium vapor in the cell could be measured.

The ratio of intensities is related to the cross section as follows (as presented by Ditchburn, Tunstead, and Yates¹⁸). The amount of light absorbed in passing through the thickness dx of the vapor at pressure p is given by

$$dI = - \beta p I dx \quad I-16$$

where I is the initial light intensity and β is the absorption coefficient for unit pressure which is related to the atomic cross section σ_a by

$$\beta = \sigma_a \frac{1}{760} \frac{273}{T} N \quad I-17$$

where T is the absolute temperature and N is the number of particles per cubic centimeter at 273 °K and 760 torr.

If the temperature is the same in all parts of the absorbing

cell, and p is a known function of x , equation I-16 may be integrated in the form

$$\ln \frac{I_0}{I} = \beta \int p \, dx \quad . \quad \text{I-18}$$

It is convenient to calculate the "equivalent length," L_a , of the absorbing column, which is defined to be a column of vapor at constant pressure (P_a) which produces the same absorption as the actual column -

$$L_a = \int p \, dx / P_a \quad . \quad \text{I-19}$$

A simple diffusion model is used to find a form for $p(x)$ which is then integrated to determine L_a . The final form of equation I-18 is

$$\ln \frac{I_0}{I} = \sigma_a N \frac{273}{T} \frac{P_a L_a}{760} \quad . \quad \text{I-20}$$

In order to determine the atomic cross section, σ_a , the ratio I_0/I must be measured as already discussed. Further, the tube temperature, T , and the vapor pressure, P_a must be determined.

This last quantity, P_a , is not well known. Although the recent determinations of vapor pressures are presumably fairly accurate, the possibility of significant errors from this source is certainly real. To give an indication of the spread of the vapor pressure data in the literature, the

values for P_a given by Stuhl and Sinke¹⁹ (1956) differ from those listed in the J.A.N.A.F. tables²⁰ (1962) by typically 25% from 300 °K to 600 °K. Likewise the values of Honig¹² (1962) differ by an average of 15% from the J.A.N.A.F values over the same temperature range.

In addition to questions about the accuracy of vapor pressure data, another difficulty in cell measurements, where pressures are typically high, is the possibility of spurious effects due to the presence of dimer molecules, Cs_2 . In photoionization experiments on cesium, this is a particular problem. For example, at the temperatures (and hence pressures) used in the Marr and Creek experiment the partial pressure of dimers ranges from 20 millitorr to 0.2 torr.²⁰ Referenced to the atom pressure at these same temperatures, the dimer pressure is as high as 2.4% that of atoms.

The significance of this population is made apparent by considering the magnitude of the dimer photoionization cross section. Popescu et al.²¹ and Creek and Marr²² (see fig. I-16) have measured this process and report that near the atomic threshold the cross section for photoionization of dimers is as much as two orders of magnitude larger than the atomic cross section. Given this fact, and the relative dimer population noted above, it is

Figure I-16: Photoionization cross section for Cs_2 as a function of wavelength. Dashed line Creek and Marr, closed circles Popescu et al.

clear that a method must be devised to subtract out this spurious signal which may otherwise be as much as 2.5 times as large as the signal due to photoabsorption by atoms.

In order to separate the absorption due to molecules from that due to atoms, Marr and Creek rewrite equation I-20 to account for both absorption sources:

$$\ln \frac{I_0}{I} = \frac{N}{T} \frac{273}{760} \sigma_a P_a L_a \left[1 + \frac{\sigma_m P_m L_m}{\sigma_a P_a L_a} \right] \quad \text{I-21}$$

where the subscript m signifies a quantity appropriate to molecules. Chemical kinetic arguments may be used to relate P_m to P_a -

$$P_a^2 = P_m K \quad \text{I-22}$$

where K is the equilibrium constant for the reaction

To the approximation that K is independent of T, the total measured cross section, ρ , (due to both atoms and dimers) has the form

$$\rho = C \sigma_a + C^2 \tau, \quad \text{I-24}$$

where C is the atomic concentration and τ is proportional to the molecular cross section. Plotting $\rho/\bar{C}$ vs. $\bar{C}$ yields a straight line, with an intercept at $C = 0$ of σ_a , the

desired quantity. This is the procedure used by Braddick and Ditchburn¹¹ (whose results were shown in figure I-14).

Marr and Creek use essentially the same procedure but use the temperature variation of K as tabulated in the J.A.N.A.F. tables²⁰ as a refinement of the method.

The results of the Marr and Creek measurement have already been shown in figures I-1 and I-14. With reference to the first of these figures, their experimental results are approximately a factor of two larger than the theoretical calculations of Weisheit¹ and Norcross.² In addition, as shown in the latter figure, there is significant disagreement among the three experimental results shown - roughly a factor of two spread in values at the cross section minimum.

There are thus many difficulties associated with the vapor cell measurements just described. These include the need for accurate vapor pressure data, difficulty in determination of the path length, and, in the case of cesium, the presence of the undesired absorption due to the photoionization of dimers.

This was the situation when it was decided to undertake a measurement of the photoionization cross section for cesium in this laboratory. The details of the apparatus and of the measurement itself will be discussed in the following chapters.

CHAPTER II

This chapter is concerned with details of the present photoionization measurement. However, since the apparatus used in this work has not been previously documented, it is necessary first to describe the component parts of the machine (Part A) after which the measurement itself will be discussed (Part B).

A. The Apparatus

(1) General. The apparatus is of conventional crossed beams design, wherein a beam of alkali atoms is intersected by the output beam of a frequency doubled laser. Ions formed by photoionization of atoms in the alkali beam are detected by an electron multiplier. Since an absolute measurement of the photoionization cross section is desired, methods have been developed for determining the intensity profile of the atom beam, for absolute measurements of the particle flux in each beam, and for absolute calibration of the particle detector.

(2) Vacuum System. A top view of the apparatus is shown in figure II-1. As seen in this scale drawing, the vacuum system comprises two chambers - a small source chamber and a larger collision chamber - separated by a

Figure II-1: Diagram of the apparatus.

differential pumping slit. The small chamber is evacuated by a 2" diffusion pump (NRC),* while the larger chamber has a 4" diffusion pump (NRC). The diffusion pumps are backed by a two stage mechanical pump (WEL). Water cooled baffles over each diffusion pump inhibit contamination of the chambers by pump oil. Additional pumping for condensibles is provided in the large chamber by a liquid nitrogen cooled finger with automatic fill control. Both chambers operate at 1×10^{-7} torr or better, the large chamber having a lower pressure owing to its higher pumping speed and smaller gas load.

The system is designed for quick access to the internal parts: (1) the oven mounts in a water cooled enclosure attached to the large lid of the source chamber, (2) the ion collector assembly mounts in a keying slot on a table attached to the large lid of the collision chamber, and (3) the alkali beam scanner and beam collector mount on a 9" conflat flange. Alignment of the various internal pieces is easily accomplished by putting the appropriate vacuum flange in place and rotating it to the proper (marked) position.

In an effort to make the machine as flexible as

* Equipment manufacturers are indicated by a three letter code in parentheses. See Appendix A for detailed information.

possible for use in other experiments, a novel method for location of feedthroughs has been used. On each of the lids for the two chambers are a number of locations for attachment of 2 3/4" conflat flanges (VAR, HUN), which may be purchased with virtually any type of feedthrough as an off-the-shelf item. The vacuum seal between the conflat flange and the chamber lid is maintained by a viton O-ring located just outside the knife edge, which is normally the sealing surface for the conflat flange. This system has, despite its ungainly appearance, proven itself to be trouble free and quite versatile.

(3) The Oven. Figure II-2 shows an isometric view of the internal elements of the system. The beam issues from an oven, which is shown in the lower left hand corner. The oven body made of stainless steel comprises a reservoir occupying the rear half of the body which connects to the nose of the oven by a 0.25" diameter bore. A large copper cap on the nose seals the bore, save for a 0.043" diameter orifice, from which the beam effuses.

The procedure for loading the oven is quite simple. A vial (see figure II-3) containing the alkali metal (CAL) is placed inside the oven which is itself located in a nitrogen filled dry bag. The vial is broken at the neck and the oven sealed and mounted on its platform. The

Figure II-2: Schematic of the apparatus.

Dimensions (mm)	d	h_1	h_2
1 gm vial	11	22	30
5 gm vial	17	37	73

Figure II-3: Sketch of the alkali metals vials.

chamber lid, with platform and oven attached, is put in place on the apparatus and the system pumped down. The entire procedure requires approximately 5 minutes between cracking the vial and turning on the mechanical pump. Another 5 minutes is required before power is applied to the diffusion pumps. Contamination of the alkali by chemical reactions (with water for example) is not expected since only a small area of metal is exposed, and even that small amount is exposed almost entirely to nitrogen.

Once the system has pumped down, the oven may be heated to form a beam. The heating is controlled by two separate circuits, one for the nose of the oven and the other for the body. Each circuit consists of a suitably located iron-constantan thermocouple to measure the temperature of the oven and an electronic controller used to regulate the power supplied to each set of heater elements in order to maintain a preset temperature. A description of the regulator circuit is contained in Appendix B.

The heating elements are made by forming 0.010" tantallum wire (MAC) into spirals that fit into the many holes in the oven - there being 10 holes each for body and nose heaters. Each spiralled segment is insulated from the oven body by a piece of thin-walled alumina tubing (VEN). The heater segments are hooked together in series-parallel

connections to obtain a convenient resistance - about 20 ohms for each of the two circuits.

To start the beam, the heaters are turned on to bring the nose to 100-150 °C and the body to a slightly lower temperature. At this relatively high temperature the impurities are driven off and the cesium metal is transferred from the vial to the reservoir. Once the alkali beam intensity has stabilized, the controller is set to bring the nose temperature to 50-80 °C, and the body heaters turned off. Since the oven cools almost entirely by radiation, the approach to the lower temperature is slow and generally requires several hours.

In the normal running configuration, with only the nose heaters working, it is observed that at a nose temperature of 50-80 °C, the body is typically 5-10 °C cooler. This temperature difference has been found sufficient to prevent clogging of the oven orifice by condensation of alkali vapor.

Details pertaining to the effusion process by which the beam is formed are to be found in Appendix E which also includes a list of references for vapor pressure data.

(4) The Alkali Beamline. Mounted immediately in front of the oven are a pair of apertures that provide some initial collimation to the beam. Between the

apertures is a space intended for placement of a chopper wheel for modulating the beam. Such a device was not necessary for the present experiment and so has not yet been built.

Also located between the apertures is a beam flag which may be moved by a rotary drive so as to intercept the beam when desired.

(5) The Interchamber Valve. The beam enters the collision chamber through a hole in the top hat. It was found, after prolonged periods under vacuum, that adjacent stages of the particle detector (located in the collision chamber) were being shorted together by deposits assumed to be cesium. In response to this problem, a simple sliding valve was installed in the top hat and is used to isolate the two chambers when the apparatus is not in use, thus minimizing the transport of cesium into the collision chamber. Following this, no further shorting of the multiplier stages has been experienced.

(6) Beam Defining Apertures. Mounted on the ion collector assembly in the collision chamber is a fixed dimension aperture that normally provides the final collimation to the beam. For some purposes, however, it is desirable to change the beam width and/or beam flux. This is accomplished using a variable aperture which has

been incorporated into the apparatus. Located immediately in front of the fixed aperture is a tab which may be moved horizontally to intercept a part of the beam that would otherwise be transmitted through the fixed aperture. The tab is attached to an aluminum-bronze slider that is driven by a 28 thread/inch screw which may be rotated from outside the vacuum system. The variable aperture was used for diagnostics in the multiplier calibration experiment to be described in Section B of this chapter.

(7) The Ion Collector Assembly and Detector. After collimation the beam enters the ion collector assembly (see figure II-4) where it may be crossed by the laser beam (see paragraph 9, this section) or intercepted by the calibration wire (Section B, paragraph 2). Ions formed in the interaction region are extracted downward by a field of approximately 50 V/cm, travel through a series of grids, and strike a Johnston multiplier after being accelerated to an energy of 5 keV. Pulses from the multiplier are amplified external to the system and counted.

For reasons associated with the calibration experiment, the first dynode of the multiplier is normally operated at ground potential. This necessitates that the anode of the multiplier be operated at a voltage of $\sim + 5$ kV which in turn requires that the output pulses be capacitatively

Figure II-4: Ion collector assembly.

coupled to the external amplifiers and counting electronics. The coupling network, together with the RC-filters to attenuate RF noise picked up on the high voltage power line, is shown in figure II-5.

Pulses from the anode of the multiplier are coupled out through this network to a series of amplifiers (LRS) which provide a variable gain of one- to three-hundred. The output from the amplifiers is sent to the discriminator (EGG) and hence to a scaler (EGG, CAN). The operation of the electronics is completely conventional and will not be discussed further.

There is a radio frequency (100 MHz) noise source that affects virtually every apparatus in the laboratory. The origin of the noise is unknown, but its presence requires that particular care be taken both in particle counting measurements and in current measurements. In an effort to reduce difficulties associated with the presence of this source, the apparatus was grounded to the frame of the building using a low inductance strap. Counting measurements were further improved by mounting one amplifier stage as near as possible to the feedthrough for the multiplier anode. The best current measurements were performed running the electrometer from an isolation transformer and employing a single point ground from the electrometer head

$R_1, R_2 \sim 50 \text{ k}\Omega$
 $R_3 \sim 1 \text{ k}\Omega$
 $R_4 \sim 50 \Omega$
 $C_1, C_2 \sim 1000 \text{ pf}, 6 \text{ kV}$
 $D_1, D_2 - \text{IN914}$

Figure II-5: Signal coupling network.

to the earthing strap.

(8) The Alkali Beam Scanner and Collector. The alkali beam, after traversing the ion collector assembly, travels several centimeters before it is collected on a cooled copper plate. Immediately prior to striking the collector plate, a fraction of the atoms in the beam may be intercepted by either of two hot wire ionizers mounted on a movable scanner. Alkali atoms that strike the wire are ionized on the surface by tunneling of the valence electron into the metal. The ions subsequently evaporate from the heated wire producing an ion current. By measuring this current and knowing the geometry of the system, the total flux of alkali atoms in the beam may be determined. Appendix D discusses the biasing arrangements that allow the ion current to be easily measured.

The scanner assembly consists of two tungsten wires (MAC) 0.002" diameter ($\pm 5\%$) mounted on a stainless steel frame at right angles to each other and to the beam direction. The frame is attached to a rod that may be moved from outside the system. Figure II-6 shows the two wires and the frame as seen from the interaction region. The motion of the frame is at 45° to the wire as indicated in the figure. Starting from the centered position (figure II-6a) where neither wire intersects the beam, the frame may be

Figure II-6: Use of the scanner assembly for monitoring beam uniformity. Arrows indicate direction of scanner motion.

moved upwards and to the right as indicated in figure II-6b. This motion sweeps the horizontal wire through the beam, permitting measurements to be made of the beam intensity and uniformity.

A further use of the beam scanner is illustrated in figure II-6c - as the scanner is moved down and left from the starting position, the vertical wire sweeps through the beam from side to side. This permits the width of the beam at the scanner plane to be determined by measuring the translation required to move the wire from one beam edge to the other. This width may be compared with the size of the beam estimated from the location and dimensions of the beam aperture, which ensures against error due to (1) slit misalignment and (2) slit clogging by cesium deposition.

Another measurement made using the scanner involves the effectiveness of the alkali beam catcher. When the scanner is located as shown in figure II-6a, clearly the ion current due to atoms in the beam striking the wire is zero. It is observed however that the current measured (taking the difference between beam on and beam off) is about 5% of the full beam current, i.e., as measured in the condition shown in figure II-6b. One explanation of this behavior is that a certain fraction of the beam atoms are reflected from the catcher, strike the wire, and are detected.

This implies that the measured current for the full beam is in error by this amount and must be corrected. An effort was made to decrease the reflection by lowering the temperature of the collector. It appears that over the rather limited temperature range covered (+10 to -20 ° est.), that little change in the reflection coefficient occurs. Another possibility is that a fraction of the beam strikes a warm part of the catcher and is thus more likely to bounce. Being a rather small effect, it was not pursued at length since even a 100% error in the magnitude of the correction would change the cross section by only 5%.

(9) The Laser. The laser system used in this experiment consists of a frequency doubled dye laser pumped by a nitrogen laser. The nitrogen laser is of conventional design, consisting of a high voltage capacitor bank, a spark gap trigger, and a nitrogen filled plasma tube. Lasing occurs at $3371 \text{ \AA}$, with pulse lengths $\sim 10 \text{ ns}$ and peak powers up to 800 kW at 5 pulses per second. The output of the nitrogen laser is focused into the cell contained in the dye laser cavity as shown in figure II-7. The cavity configuration shown in the figure produces a broad linewidth ($\sim 1\text{-}5 \text{ \AA}$) and efficient ($> 10\%$ conversion of nitrogen laser power to dye laser power.²³

As seen earlier in figure I-1, the wavelengths

Figure II-7: Dye laser schematic.

necessary for the photoionization experiment are in the near ultraviolet ($\lambda \leq 3180 \text{ \AA}$). To produce light in this spectral region, the output of the dye laser is frequency doubled using one of the following crystals: (1) 90° , 1 cm ADP, (2) 60° , 2.5 cm ADP, and (3) 42° , 1 cm LFM (QUA, LAS, CLE). Use of these crystals permitted the spectral region from $3250 \text{ \AA}$ (below threshold) to $2400 \text{ \AA}$ to be scanned. Figures II-8 and II-9 show tuning curves obtained in this laboratory^{24,25} which indicate roughly the amount of power available with these crystals using a laser system similar to that described above.

The beam of ultraviolet radiation is transported to the apparatus by a set of UV reflective mirrors (SPC, ORI) and enters (and exits) the machine through fused quartz windows (WOR).

The average laser power is measured immediately in front of the entrance window to the apparatus using a calibrated thermopile (EPP). The number of photons entering the apparatus per second is easily calculated knowing the average power, the wavelength, plus assorted physical constants (see Section B, paragraph 4).

A problem that affected the previous cell measurements was degradation of the windows due to alkali deposition. Although this seemed a rather unlikely problem in the

Figure II-8: Tuning curves for ADP.

Figure II-9: Tuning curves for LFM.

present experiment, a comparison was made between the photon flux entering the apparatus and that emerging from the machine. After correcting for reflection losses (easily calculated for normal incidence²⁶) the two fluxes were observed to be equal to within the certainty of the measurement. (These measurements were performed two ways - using a helium neon laser giving high accuracy, and using the UV beam giving lower precision but with the virtue of being at the same wavelength as required for the photoionization experiment.)

This completes the description of the basic apparatus. The following section describes the photoionization measurement and explains the method for determining the photoionization cross section from measured parameters.

B. The Measurement

The usual small signal expression is used to determine the photoionization cross section σ (cm²) from measured parameters

$$\sigma = S / k n_2 I \ell_2 . \quad \text{II-1}$$

Here S is the number of photoions counted per second (#/sec) by a multiplier of counting efficiency k . The number density of cesium atoms in the illuminated region

is n_2 ($\#/cm^3$), the number of photons passing through the atomic beam per second is I ($\#/sec$), and the path length that the photon beam travels through the atom beam is l_2 (cm).

(1) The photoion Signal. Figure II-10 shows the timing sequence used in the experiment. A laser triggered command (a) is generated every 200 ms (5 Hz). A short time ($\sim 1 \mu s$) after each trigger command, the laser fires (indicated in (b) by the RF noise seen on the oscilloscope), and the interaction region is illuminated by the UV radiation from the dye laser. Ions formed by the passage of the light beam are swept toward the particle multiplier and arrive there $\sim 4 \mu s$ later (d) by which time the discriminator has been turned on (c). Pulses from the multiplier are amplified as previously described (Chapter II, Section A, paragraph 7), shaped by the discriminator, and counted.

In order to extract the count rate due to the desired photoion signal, S , from the count rate due to other sources, it is noted that in a two beam experiment such as this, there are in general four sources of counts. These are:

(1) that due to the passage of the laser beam through the chamber (creating surface ions, photoions from background gas, etc.), denoted L , (2) that due to cosmic rays, RF

Figure II-10: Timing sequence:

- (a) N_2 -laser trigger command
- (b) radio frequency noise from laser firing
- (c) discriminator gate
- (d) photo-ion arrival time.

noise, ion gauges, etc., denoted N, (3) that due to the interaction between the two beams producing the desired photoions (S), and (4) that due to the passage of the alkali beam through the chamber, denoted A, but expected to be small and included here only for completeness. The following table (II-1) indicates when each of these sources contributes to the measured count rate. For each case, labeled a, b, c, or d, a corresponding count rate S_i is measured. It is easily verified that

$$S = S_a + S_d - S_b - S_c , \quad \text{II-2}$$

so that the desired signal may be determined by interrupting the beams as indicated in the table and forming the above sum.

It is appropriate here to mention the relative sizes of the atom count rates. With reference to a typical run, the largest count rates were S_a and S_c . S_b and S_d were generally small, only 6% of S_a and being approximately equal and entering Eq. II-2 with opposite sign, would contribute only a 2% error if both were completely ignored. The single most important source of background counts was due to the photoionization of residual cesium in the chamber, i.e., to L, which affects both S_a and S_c . At room temperature, the vapor pressure of cesium is sufficient that the density

Table II-1

S_A	S_B	S_C	S_D
Cesium on	Cesium on	Cesium off	Cesium off
Laser on	Laser off	Laser on	Laser off
S, L, A, N	L, N	N, A	N

of residual cesium ($\sim 3 \times 10^{10}$) is four orders of magnitude larger than in the beam itself ($\sim 1 \times 10^6$) with obvious implications for the signal to noise ratio. It was in part for this reason that the liquid nitrogen cold trap was installed in the chamber. This addition greatly increased the pumping speed for cesium with substantial improvement in signal to noise ratio resulting.

It is to be noted that total collection of the photoions must be obtained to perform the experiment accurately. Normally a field of 50 volts/cm is applied to extract the ions from the interaction region. Since the cesium atoms in the beam are thermal, this field is certainly adequate to give 100% collection of the ions, but the collection field was nevertheless doubled with no change in photoion signal indicating the attainment of complete collection.

A problem that is particularly troublesome when doing experiments with a nitrogen laser system is due to the dead time of the counting electronics. While the average laser power is low, the instantaneous power during the laser pulse is a factor of $\sim 10^7$ - 10^8 times larger - often tens of kilowatts or better. With such high powers, it is not uncommon to produce many ions during a single pulse. Unfortunately since all these ions are formed at essentially the same time and place, they all reach the multiplier

at the same time. Since even the fastest counting systems have dead times (~ 40 ns) longer than the spread in arrival times of the ions (as small as ~ 5 ns, the laser pulse length), it is not generally possible to count more than one ion per laser shot. Correction factors may be derived²⁷ to adjust the measured count rate for this effect, but as long as the signal to noise ratio is not significantly decreased, less error is introduced by operating at low count rates so that the probability of producing more than one ion per laser shot is negligible. With reference to the cited calculations of West,²⁷ an average count rate of 0.1 per laser pulse requires a 5% deadtime correction while for a rate of 0.3 per laser pulse a correction of 20% is necessary.

In performing this experiment, the maximum count rate was constrained to always be less than 0.1 per laser pulse and no dead time correction applied. The validity of the procedure was verified by decreasing the laser intensity with the insertion of neutral density filters in the beam and measuring the count rate. The linearity of count rate with variation of laser power was taken as sufficient to justify neglect of the dead time correction.

(2) The Multiplier Calibration. In general, for a given number, m , of ions that strike a particle multiplier,

a different number, m' , of output pulses are produced. If the arrival rate of ions is low enough that the dead time of the system may be ignored, then the ratio m'/m is known as the counting efficiency and is designated in this thesis as k . The counting efficiency ranges in magnitude from zero to one, being large for light ions at kilovolt energies (~ 0.95)²⁸ and decreasing for heavier ions of a given incident energy. Although the literature contains reports of many studies²⁹ of quantities related to the counting efficiency, it is generally agreed that the results are useful only as guides and should not be taken as invariant. The usual procedure is thus to perform an in situ measurement of the efficiency for the particular system of interest.

The method for doing this calibration is straightforward in the present apparatus. As previously noted (Section A, paragraph 7), a hot wire ionizer is located at the interaction region (see also figure II-2) and may be placed in the alkali beam in the position traversed by the laser beam. Cesium atoms that strike the wire are ionized on the surface and subsequently evaporate from the wire and are transported to the particle multiplier.

If the interaction region (including the hot wire ionizer) is operated at a potential of + 5 kV, then the

first element of the particle multiplier may be operated at ground potential while still permitting high impact energies to be obtained.

The current to the grounded multiplier was measured using a vibrating reed electrometer (CAR). The number m of ions incident per second is related to the measured current j by

$$m = j/e \quad \text{II-3}$$

where e is the electron charge.

The multiplier is then turned on by applying a voltage (typically 4.5 - 5.0 kV) to the last element of the dynode chain. Pulses are then counted and the measured rate m_r is corrected for the dead time τ using³⁰

$$m' = m_r / (1 - m_r \tau)$$

where m' is the count rate that would be measured if the system had negligible dead time.

The system deadtime was determined as follows - the output pulse width of the discriminator was set to be many times longer than the normal pulse width of the multiplier. In this case, the total deadtime is essentially equal to the output pulse length of the discriminator which may be measured using an oscilloscope with a calibrated time base.

Typical count rates for the calibration procedure were 2×10^5 /sec with the dead time set to be 400 ns. For these conditions the dead time correction is only 9%. Note that the dead time correction is not sensitive to the value of the dead time, τ , used and that even a 20% error in this quantity does not change the value of m' by more than 3%.

The efficiency of the multiplier is given by

$$k = m'/m \quad \text{II-5}$$

$$= \frac{e}{j} \frac{m_r}{1 - m_r \tau} \quad \text{II-6}$$

The procedure outlined above is valid so long as two saturation conditions are met. The first of these is that secondary electron emission from the multiplier is suppressed with no loss to nearby electrodes. As the ion collector assembly was configured in this experiment, a grid was located ~ 0.25 inches away from the first element of the multiplier. It was found that by varying the bias on this grid from ground (the nominal potential of the first element of the multiplier) to -60 volts (to repel secondaries back to the multiplier) that approximately a 20% change in both current measured and particles counted was obtained. Beyond -60 volts no further change in these quantities was measured and accordingly a potential of

-80 volts was applied to that grid for all measurements. This behavior, altering the count rate by small external fields, is contrary to the information provided in the Johnston multiplier handbook³¹ wherein it is implied that application of such fields is not necessary to attain maximum detection efficiency.

The second type of saturation behavior necessary for accurate multiplier calibration is that the system gain be large enough that every incident ion that ejects one or more secondary electrons is counted. This is achieved by increasing both the gain of the multiplier and of the external amplifiers until the count rate reaches a plateau indicating that the saturation condition is satisfied. The gain conditions necessary to saturate the count rate in these circumstances are also used in the photoionization measurement, ensuring that the measured value of k is applicable to that experiment.

If the multiplier efficiency k is to be considered absolute, the electrometer must be calibrated. This has been done recently,³² but is not required for the experiment reported in this thesis provided the same input resistor and range scales are used in both the measurement of k and of the alkali beam density n_2 . (As will be seen in the following paragraph, determination of n_2 requires

the measurement of the ion current leaving a hot wire ionizer.) Accordingly the same input resistor was used for all current measurements. The different ranges of the electrometer were shown to be internally consistent so that no significant error was introduced by using more than one range of the electrometer. The average value of k determined was $k = 0.62 \pm 5\%$ for 5 keV cesium incident on the copper-beryllium multiplier, using the electrometer calibration of Nitz.³²

(3) The Alkali Beam Density. The density, n_2 , of the cesium beam at the interaction region is determined by use of the scanning hot wire detector. As described in Chapter II, Section A, paragraph 3, cesium atoms strike the wire, ionize on the surface, and subsequently evaporate, producing a current, i , of cesium ions. The number density, n_2 , of atoms at the interaction region is then determined from

$$n_2 = ig(\overline{1/v})/e\delta \quad \text{II-7}$$

where g is a geometric factor related to the dimensions of the beam and the size of the hot wire ionizer, e is the electronic charge, and δ is the surface ionization efficiency for cesium on the tungsten wire. The mean reciprocal velocity $(\overline{1/v})$ of the beam atoms is calculated

using a Maxwellian velocity distribution modified by an extra factor of v to account for the effusion process which preferentially produces fast atoms.³³ The derivation of this equation is straightforward and is given in Appendix C.

It is to be noted that under some conditions the use of the modified Maxwellian distribution is not valid. For example, Hall and Zorn³⁴ have reported on the effect of collisions between beam particles and background gas which preferentially remove slow atoms from the beam. In electric deflections experiments such as theirs, an extremely well collimated beam traverses a long distance ($\sim$ two meters) in typical high vacuum conditions ($\sim 7 \times 10^{-8}$ torr). Since the amount of deflection experienced by an atom is directly proportional to the amount of time spent in the inhomogeneous field, a systematic depletion of slow atoms by even a few percent can result in 10 to 20% errors in the measured quantity (the static polarizability in this case).

Another circumstance, and perhaps more familiar, where such depletion effects are important is in the case of intense beams. It is then possible to violate the assumptions implicit in the effusive flow criterion - that the region outside the oven be a "perfect vacuum", i.e., that no collisions occur between beam particles.

Clearly the occurrence of such effects in the present

experiment would result in an error in the value of $(1/v)$ and hence in the cross section result. In an effort to estimate the maximum error that would result from a systematic loss of slow atoms from the beam, the work of Hall³⁵ has been examined. He measured the velocity distribution of a cesium beam formed by effusion from a standard oven. The beam was carefully collimated and velocity selected using a multi-bladed beam chopper. After traveling approximately 2 m in vacuum, the beam was detected by use of a hot wire ionizer. By measuring the flux of atoms as a function of atomic velocity, the velocity distribution of the beam was determined. The results, in graphical form, were supplied by Dr. B. Bederson, N.Y.U. From the information provided, a distribution of the form

$$f(v) dv \propto v^N \exp[-mv^2/2kT] \quad \text{II-8}$$

was fit to the data, using the procedure outlined by Dunning et al.³⁶ (In this equation, $f(v)dv$ is the flux of atoms having velocity between v and $v + dv$, m is the atomic mass, k is Boltzmann's constant and T is the absolute temperature of the oven.) The parameter N is adjusted to reproduce the measured distribution. After choosing N the value of $(1/v)$ for this distribution was calculated and compared with that for a pure effusive source. The

difference in $(\overline{1/v})$ for the two cases was 25%, the actual distribution yielding the smaller value as expected. If these results applied to the present experiment, the cross section calculated assuming simple effusive flow would be too small by 25%. In fact, the work of Hall applies to a situation so extreme as to represent clearly worst case conditions vis-a-vis the present experiment. The beam, in this work, is a factor of 7 shorter than in Hall's experiment. Further, the angular divergence of the present beam is quite large, so that small scattering angle collisions do not remove cesium from the beam as they do in Hall's case. Finally, the cesium pressure in the present oven is between 1 1/2 and 2 orders of magnitude lower than in the Hall experiment which greatly reduces the number of beam-beam collisions which also affects the velocity distribution of the beam.

This evidence, together with the supportive evidence reported in the work of Miller and Kusch³⁷ is offered to indicate that the velocity distribution of the beam in this experiment is determined by the effusion process and is not significantly altered by collisions occurring outside the oven.

The quantity δ (the surface ionization efficiency) in equation II-7 has been extensively investigated for the

alkali metals first by Langmuir and co-workers³⁸ and more recently by Datz and Taylor.³⁹ The latter work reports measurements of the ionization efficiency for each of the alkalis on various surfaces. Shown in figure II-11 is a graph of surface ionization efficiency for several species on tungsten, as a function of wire temperature as reported by Datz and Taylor. Notice that for cesium atoms incident on tungsten, the process is 100% efficient over a broad range of temperatures. Observe also that the ionization efficiency curve has a very distinctive shape, rising very rapidly from zero, reaching 100% at $\sim 1100^{\circ}\text{K}$ and then remaining essentially constant out at least to 2200°K . The reasons for this behavior are beyond the scope of this thesis but the behavior of the current of cesium ions leaving the wire with temperature variation has become a standard test to verify that the hot wire ionizer is working properly, is of the proper material, etc. This test has been performed in the present apparatus for cesium, with results in complete accord with the Datz and Taylor findings of figure II-11.

(4) The Photon Flux. The photon flux I is determined from measurement of the average laser power (using a thermopile) and knowledge of the wavelength (found using a spectrometer) (JAR, SPE). The photon flux is equal to

Figure 11-11: Ionization of alkali metals on tungsten.

the energy input per second divided by the energy per photon. The former is given by

$$P = K V \quad \text{II-9}$$

where P is the average power (joules/sec), K is the calibration factor of the thermopile ($\mu\text{W}/\mu\text{V}$), and V is the measured thermopile output voltage (typically 10's of microvolts). The energy per photon, E_λ (joules) is

$$E_\lambda = \frac{1}{\lambda \times 10^{-8}} \frac{1.6 \times 10^{-19}}{8066} \quad \text{II-10}$$

where $(\lambda \times 10^{-8})^{-1}$ is the photon energy in cm^{-1} , the factor $1/8066$ converts from cm^{-1} to electron volts, and there are 1.6×10^{-19} joules per eV. The number of photons per second is thus

$$I = P/E_\lambda \quad \text{II-11}$$

$$= \frac{V}{\lambda \times 10^{-8}} \frac{1.6 \times 10^{-19}}{8066} \quad \text{II-12}$$

The thermopile calibration supplied by the manufacturer was checked by comparing this device with another similar thermopile in the laboratory. Measurements of the power output of a helium neon laser were performed using both thermopiles with identical results. This result strongly

suggests that the calibration factor of each thermopile has not changed since it was last measured. Likewise, the electrometer used to measure the thermopile output was compared with another instrument, with no measurable difference in calibration detected.

(5) Path Length. The path length, l_2 , traveled by the photon beam in traversing the atom beam is determined by the location of the beam defining aperture relative to the oven orifice and by the dimensions of the aperture. Appendix C includes a discussion of beam geometry necessary to calculate the path length.

As a check, the beam scanner may be used to determine the path length (beam width) in situ. (see Section A, paragraph 8 of this chapter) ensuring against error due to slit misalignment and to narrowing of the slits due to cesium deposition. Again the details of the geometry are contained in Appendix C. Measurement of the beam width using the beam scanner was performed several times during the course of the experiment, with no evidence of either misalignment or clogging observed.

CHAPTER III

A. Results and Sources of Error

The results of this experiment are shown in figure III-1 together with the previously measured results of Marr and Creek³ and the calculations of Weisheit¹ and of Norcross.² The values shown for this work are the average of several measurements at each of the indicated wavelengths. The error bars are computed as the algebraic sum of the standard deviation of the mean plus 20% of the mean, the latter quantity representing the estimated systematic uncertainty in the measurement

Systematic errors may affect the cross section determination in several ways. The following sources are expected to be the most important: (1) Systematic error in the multiplier calibration, (2) Systematic error in the beam density determination due to uncertainty in the surface ionization efficiency, δ , and in the diameter of the hot wire ionizer used in the beam scanner, and (3) Systematic error in the laser power measurement. In addition, a number of lesser systematic errors may be present, each on the order of 1% and totaling no more than a few percent.

In estimating the systematic error in the multiplier calibration, it should be recalled that the currents measured in the multiplier calibration procedure and in the

Figure III-1: Summary of atomic cesium photoionization work. — experiment of Marr and Creek; — calculation of Weisheit; — calculation of Norcross; this work.

alkali density determination are not required to be absolute since the expression for the cross section requires only the ratio of these two currents to be known. The total systematic uncertainty in the multiplier calibration is thus estimated at 3-5% due principally to the dead time correction.

The systematic uncertainty in the alkali density is due in part to error in δ , which is estimated to be known to within 5%. In particular, although Datz and Taylor report $\delta = 1$ for cesium incident on a tungsten wire, Nygaard⁴⁰ has performed studies using a quartz microbalance to measure the rate of deposition of cesium by an impinging beam. Comparing the beam flux calculated by that method with the results obtained using a hot wire ionizer, he concludes that $\delta = 0.95$, a result 5% different from that of Datz and Taylor. It is to be noted however that the microbalance technique is sufficiently difficult that a 5% error is not unreasonable.⁴¹ The present results are calculated assuming $\delta = 1.00$, with a systematic uncertainty of 5%. Clearly, the reported cross section may be altered at a later date when the situation is more clear.

The alkali density determination is also affected by uncertainty in the diameter of the hot wire ionizer which is mounted in the beam scanner assembly. As shown in

Appendix C, the wire diameter enters directly into the calculations so that the 5% uncertainty in the wire size manifests itself as an equal uncertainty in the alkali density. In addition a 3% error is included in the density determination to allow for uncertainty in the quantity $(1/v)$ as discussed in Chapter II, Section B, Paragraph 3.

Systematic error in the laser power measurement enters by way of the calibration of the thermopile (see also Appendix E) and the microvoltmeter. Both devices were factory calibrated, and as discussed in Chapter II, compared with other calibrated devices in the laboratory, with no discrepancies discovered. The total estimated systematic error due to these devices is thus taken to be 5%.

B. Discussion of Results and Comparison with Previous Work

As previously discussed (in Chapter I, Section C), the photoionization cross section for cesium dimer molecules (Cs_2) is approximately one hundred times larger just below the atomic threshold than the atomic cross section is at threshold. Further, as shown by Creek and Marr²² (see figure I-17) the dimer photoabsorption cross section is larger in this region than in any other part of the spectrum. A cross section measured below the atomic threshold may thus be interpreted as representative of the maximum contribution

to the atomic cross section (above threshold) due to photoionization of dimers. With reference to the figure, the maximum contribution due to this source is $0.3 \times 10^{-20} \text{ cm}^2$ while the atomic cross section ranges from $\sim 10 \times 10^{-20}$ at threshold to $2.1 \times 10^{-20} \text{ cm}^2$ at $\sim 2700 \text{ \AA}$. Thus even in this worst case the error in the measured cross section is at most 15% and, given the shape of the dimer photoabsorption cross section shown earlier (figure I-17) is probably less than 5% over most of the wavelength range shown in figure III-1.

Comparing the present results with those of Weisheit¹ and Norcross,² there is clearly very good agreement. The error bars on the present results encompass both of the theoretical results at each wavelength for which the cross section was measured so that it is not possible to distinguish between the two calculations in this way. As noted in Chapter I, however, there is in any event very little to differentiate the two calculations as far as the physics of photoionization is concerned, those differences that do exist being primarily in mathematical detail.

The present results are not consistent with those of the previous measurements by Marr and Creek.³ Given the agreement between the present results and the theoretical work just noted, it would seem that the Marr and Creek

work is in error. As discussed in Chapter I, the source of such error is not obvious but several possibilities have been offered. These include uncertainties in the vapor pressure data, improper or incomplete subtraction of the photoabsorption due to dimers or perhaps in calculation of the path length through the cell.

In conclusion, the results of the present experiment are in good agreement with theoretical calculations and are not compatible with previous measurements of the process.

C. The Future

Work is now underway to use the apparatus developed during the course of the present experiment in a different set of studies. Sodium atoms are to be excited to states of high principal quantum number. Atoms in these excited states have been the subject of studies in this laboratory for several years. Greg Foltz is preparing to use the new apparatus in further work on these high Rydberg atoms, and is planning to measure the cross section for ionization of the high Rydberg atom by charged particle (electron) impact. Other experiments, including studies of collisions that change the principal quantum number and/or the orbital angular momentum, will follow.

There are also some interesting problems involving

photoexcitation of ground state cesium that may be investigated. Without going into great detail, the same cancellation in the matrix element that is responsible for the cross section minimum in the photoionization spectrum may also affect the transition moments to the different J states (from the ground state) for principal quantum number $n \sim 20$. Using different methods, various groups have reported contradictory results for their measurements of this phenomenon. It appears likely that techniques available in this laboratory could help solve the problem.

Another area where the literature is not consistent involves the structure of cesium dimers. There is conflicting evidence about the ionization potential of the molecules, and a factor of two uncertainty in the photoionization cross section for dimers just below the atomic threshold. Such work should be straightforward to do with this apparatus.

In short, there are a variety of experiments that might well be performed using the apparatus, and it appears likely that the machine will not be idle for some time to come.

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APPENDIX A

Manufacturers

CODE	EQUIPMENT	COMPANY	PAGE CITED
CAL	Alkali metal	Calery Chemical Co. Calery, PA 16024 (412)-538-3510	29
CAN	30 MHz scaler	Canberra Industries, Inc. 45 Gracey Ave. Meriden, CT 06450	34
CAR	Electrometer model 401	Cary Instruments 2724 South Peck Road Monrovia, CA 91016	46
CLE	Crystals	Cleveland Crystals	38
EGG	Discriminator Decade scaler	EG&G/Ortec 100 Midland Road Oak Ridge, TN 37830	34
EPP	Thermopile	The Eppley Laboratory Newport, Rhode Island NY 02840	38
HUN	Flanges	Huntington Laboratories 1400 Stierlin Road Mountain View, CA 94043 (415)-964-3323	29
JAR	Spectrometer	Jarrell Ashe 590 Lincoln Street Waltham, MA 02154	53
JOH	Multiplier	Johnston Laboratories 3 Industry Lane Cockeysville, MD 21030	47
LAS	Crystals	Lasermetrics, Inc. 19 Leekon Place Rochelle Park, NJ 07662	38
LRS	Pulse amplifiers	LeCroy Research Systems 126 N. Route 303, West Nyack NY 10994, (914)-358-7900	34

MAC	Wire	A. D. MacKay, Inc. 198 Broadway, New York NY 10038	30,35
NRC	2", 4" Diffusion pumps	NRC/Varian, Vacuum Div. P. O. Box 6098 Richardson, TX 75080 (214)-235-4586	28
ORI	Optical components	Oriel Corp. 1 Market Street Stamford, CT 06902 (203)-357-1600	38
QUA	Crystals	Qunatum Technology, Ltd. 60 Nugget Ave., Unit 5 Agincourt (Toronto) Ontario, Canada M1S 3A9 (416)-293-3344	38
SPC	Optical components	Special Optics, Inc. Box 163 Little Falls, NJ 07424 (201)-785-4015	38
SPE	Spectrometer	Spex Industries, Inc. P. O. Box 798 Metuchem, NJ 08840	53
VAR	Flanges	see NRC	29
VEN	Alumina	Ventron/Alfa 152 Andover Street Danvers, MA 01923	30
WEL	Mechanical pump	Sargent-Welch Scientific Co. Vacuum Products Div. 7300 Linder Ave Skokie, IL 60076 (312)-677-0600	28
WOR	Quartz windows	Worden Quartz 6121 Hillcroft Houston, TX 77036 (713)-774-2533	38

APPENDIX B

Oven Controller

The oven temperature is maintained at a preset level by an electronic controller which monitors the oven temperature and regulates the amount of power supplied to the oven heaters accordingly. A block diagram of the controller is shown in figure B-1.

The thermocouple, attached to the oven, generates an EMF that is proportional to the oven temperature. This voltage is amplified by a factor of 10^3 (figure B-2a) and is summed with two other voltages. One of these is a sawtooth oscillator (figure B-2b) and the second is a reference voltage which is equal to 10^3 times the thermocouple EMF at the preselected temperature but having opposite sign (figure B-2c).

At a given instant, t_1 , suppose the sum of the three voltages is negative (figure B-2d). The controller takes this to mean that the oven is too cool. The summer operates with positive feedback and its output voltage swings so as to turn the output transistor full on (figure B-2e). This supplies power to the oven heater.

A short time later, at t_2 , the oscillator has changed its output sufficiently that the input to the summer is

Figure B-1

Figure B-2

positive. The controller interprets this to mean that the oven is too hot, the summer output is driven to zero and the output transistor is turned off.

If the oven is far too hot or cold, then the input voltage to the summer never changes sign and the output transistor is always either full on or full off. As the oven approaches the preset temperature the summer input will change sign for an increasingly large fraction of the oscillator period. Finally when the power input to the oven is equal to the power lost, the controller will settle to a constant duty cycle and the oven temperature will not change further.

APPENDIX C

System Geometry

In chapter II, the equation

$$n_2 = i g (\overline{1/v}) / e \delta \quad \text{II-7}$$

was presented without a derivation. Recall that n_2 is the number density of cesium atoms at the interaction region, i is the current of cesium ions evaporated from the hot wire ionizer located on the beam scanner, g is a geometrical factor, $(\overline{1/v})$ is the mean inverse velocity of the beam particles, e is the electron charge, and δ is the surface ionization efficiency.

Figure C-1 shows the geometry of the system. The oven orifice is located at $r = r_0 = 0$. The effusing beam is collimated at the beam defining aperture of width ℓ_1 located at $r = r_1$ (mounted on the ion collector assembly). The laser beam intersects the alkali beam at $r = r_2$, at which point the beam width is ℓ_2 . The beam is sampled by the hot wire ionizer at $r = r_3$ where the beam width is ℓ_3 .

Simple geometry gives the result that

$$\frac{\ell_1}{r_1} = \frac{\ell_2}{r_2} = \frac{\ell_3}{r_3} \quad \text{C-1}$$

where ℓ_1 has been assumed to be the beam defining aperture.

Figure C-1: Geometry of the system.

This immediately gives equations for ℓ_2 and ℓ_3 :

$$\ell_2 = \ell_1 r_2 / r_1 \quad \text{C-2}$$

and

$$\ell_3 = \ell_1 r_3 / r_1 \quad \text{C-3}$$

Note that C-2 allows the beam width at the interaction region to be calculated as required in equation II-1.

Now let F_3 be the flux of cesium atoms per unit area ($\#/\text{sec-cm}^2$) at the scanner plane. Those atoms that strike the wire are ionized on the surface with efficiency δ and evaporate to produce a current (amperes) given by

$$i = F_3 \ell_3 d e \delta \quad \text{C-4}$$

where d is the diameter of the hot wire ionizer, and ℓ_3 is the length of wire illuminated by the beam.

In order to relate this to the number density n_2 at the interaction region (r_2), note that the relationship between the flux per unit area at r_2 and at r_3 is

$$\frac{F_2}{r_2^2} = \frac{F_3}{r_3^2} \quad \text{C-5}$$

Solving this for F_3 and using equation C-3 for ℓ_3 , equation C-4 becomes

$$i = F_2 \frac{r_2^2}{r_1 r_3} \ell_1 \text{ d e } \delta \quad \text{C-6}$$

The relationship between the flux of atoms per unit area and the number density is found by noting that

$$F_2(v) \, dv = n_2(v) \, v \, dv \quad , \quad \text{C-7}$$

where

$$F_2(v) \, dv = F_2 \, f(v) \, dv \quad \text{C-8}$$

is the flux of atoms per unit area having velocity between v and $v + dv$. The function $f(v) \, dv$ is given by a Maxwellian velocity distribution weighted⁴² by an extra factor of v to account for the effusion process:

$$f(v) \, dv = C \, v^3 \exp(-mv^2/2kT) \quad . \quad \text{C-9}$$

The normalization factor is determined by the condition that

$$\int_0^{\infty} f(v) \, dv = 1 \quad \text{C-10}$$

Some useful results for performing this type of integral will be presented toward the end of this appendix.

Solving equation C-7 for $n_2(v) \, dv$ and using C-8 gives

$$n_2(v) \, dv = F_2 \frac{1}{v} f(v) \, dv \quad \text{C-11}$$

This may be integrated over all velocities to give the total number density

$$n_2 = F_2 \int_0^{\infty} \frac{1}{v} f(v) dv \quad \text{C-12}$$

$$= F_2 (\overline{1/v}) \quad \text{C-13}$$

where $(\overline{1/v})$ is the mean inverse velocity for the distribution given in equation C-9.

Equation C-13 may be solved for F_2 , substituted into C-6 and the resulting equation solved for

$$n_2 = i (\overline{1/v}) g / e \delta \quad \text{C-14}$$

where

$$g = \frac{r_1 r_3}{r_2^2} / \ell_1 d . \quad \text{C-15}$$

Equations C-14 and C-15 constitute the desired result.

Table C-1 shows the values for various dimensions of the beam line.

As mentioned in the text, the beam scanner may be used to check for misalignment of apertures and clogging of slits. Equation C-3 gives the expected width of the beam at the scanner in terms of r_1 , r_3 , and ℓ_1 . This may be related to the scanner motion as follows. The scanner mounts on a rod which is pivoted so that a movement of the micrometer results in a motion of the scanner that is twice as

large. However the micrometer is oriented at 45° to the direction of both hot wire ionizers on the scanner. This means that the motion of, say, the vertical wire across the beam is slower by $1/\sqrt{2}$ than the total motion of the scanner. The net effect of the gearing ratio and the 45° drive is that the ionizers move $(2/\sqrt{2} =) \sqrt{2}$ times farther through the beam than indicated by the micrometer. Measurements of the micrometer travel necessary to move the wire through the beam have been performed and show good agreement with the results expected on the basis of geometrical arguments.

TABLE C-1

<u>dimension</u>	<u>cm</u>
r_1	11.65
r_2	16.10
r_3	25.62
d	0.0051
h_1	0.50
h_2	0.69 from equation C-2
h_3	1.10 from equation C-3

APPENDIX D

Biasing of the Beam Scanner

The beam scanner assembly is used to determine the flux of cesium atoms in the beam and hence the number density in the interaction region. It is therefore important that the elements of the scanner be biased so that the cesium ion current leaving the wire is completely collected and measured.

Using only one of the two hot wire ionizers for discussion, the electrical biasing is indicated in figure D-1. The detector wire is heated by a current I_f which may be varied by adjusting resistor R. The temperature of the wire is calculated from the work of Jones and Langmuir⁴³ knowing I_f and the wire diameter.

To ensure that the hot wire and associated collector plate are properly biased, it is required that the ion current (Cs^+) leaving the wire (I_1) be equal in magnitude to that reaching the collector plate (I_2). This condition holds providing the collector plate is the most negative element in the system and the ionizer is also biased below ground potential. The first of these conditions is obvious since otherwise it is energetically favorable for positive ions to travel other than to the collector plate. In order

Figure D-1: Biasing of the hot wire ionizer and collection plate.

to understand the second condition, it is necessary to know that the scanner frame is near the ionizer and is at ground potential. If the ionizer potential is positive, then some fraction of the ions evaporated from the ionizer will be collected on the frame instead of on the collector plate. This is energetically disallowed if the ionizer potential is negative.

Tests of the ionizer system have shown that the ratio I_2/I_1 is constant (= unity) for all values of $V_1 < 0$ (for $V_2 = -15$ V). This indicates complete collection. It is also found that I_1 is independent of V_1 as expected. Furthermore, the variation of cesium ion current as a function of ionizer temperature has been studied. Below $\sim 1100^\circ\text{K}$, the ion current is small and sensitive to temperature, while above 1100°K the current is independent of temperature. Comparison of the measured response with that shown in figure II-11,³⁹ shows good agreement indicating that the ionizer does indeed work as expected.

In normal operation the following parameters are used:

$$V_1 = -6$$

$$V_2 = -20$$

$$V_f = 6$$

$$I_f \sim 120-160 \text{ mA } (1150^\circ\text{K} - 1350^\circ\text{K}).$$

APPENDIX E

A note concerning the thermopile calibration is in order. The device, manufactured and calibrated by the Eppley Laboratory (see Appendix A), is supplied with two calibration factors. One is with a quartz window (supplied) in front of the receiver, and the other is without the window. The two differ by approximately 20%.

Although one may be inclined to measure powers with the window in place and use the window calibration factor, this is incorrect. The reason is as follows: the lamp used for the calibration has a broad spectral emission, and contains a significant amount of power at wavelengths that are not transmitted by the window. This effect accounts for slightly more than one half the difference in the calibration factors, the rest being due to reflection losses at the window surfaces. The point to be made is that the windowless calibration factor is characteristic of the thermopile itself and that the window-in calibration includes instrumental effects.

The average laser power is thus properly measured using the windowless calibration factor (with the window installed) and correcting as necessary for reflection of the laser light by the window.