AN ATTEMPT TO STUDY
IONIZING RADIATION FRONTS
IN Cs VAPOUR

by

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Criteria are developed for the design of an experiment to study steady radiation fronts in Cs vapor. According to these criteria, a pulsed light source of supposedly sufficient intensity ($\approx 10^{22}$ photons/cm$^2$-sec) and pulse length ($\approx 90\mu$s) was built, and an absorption tube for Cs vapor inside an oven was developed (through several models) which produced a maximum absorber density of $\approx 10^{18}$ particles/cm$^3$. Light and electrical probe measurements were carried out to detect ionizing radiation fronts in the cesium. While the light measurements were inconclusive due to stray light problems, the probe measurements showed that photoionization takes place but at a much lower rate than expected. A subsequent study of the light source confirmed that indeed the light source, a constricted capillary arc, driven by a $90\mu$s square current pulse, has a much lower intensity in the test section of the absorption tube than is required to drive a front. The low intensity of this light pulse rendered the initial aim of the experiment namely the study of steady ionization fronts in cesium vapor, unattainable with the available apparatus.
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Chapter 1

INTRODUCTION

There are many situations where intense radiation falls onto matter and is absorbed, thereby heating the material to high temperatures. One may think of stellar radiation hitting the surrounding interstellar matter or of intense laser radiation being focussed on small areas of target material as examples of such situations. In these cases the radiative heating leads to some motion of the heated gas. The motion can be so violent that it has in fact been proposed as the driving mechanism for a laser compression scheme to reach ultra high densities in fusion experiments.

The study of the radiation induced motion in the two examples mentioned above is complicated but for very different reasons. The initial conditions for the interstellar phenomena are only vaguely known, and the process proceeds slowly compared to our own time scales, so that we can hardly hope to witness any changes. Laser sparks, on the other hand are very transient objects of minute spherical or egg-shaped geometry in which the absorption mechanism apparently changes from multiphoton absorption to inverse bremsstrahlung and possibly to other not yet fully understood mechanisms.
In order to avoid such complications Zuzak (1) started a different line of research with the aim of studying radiation gas dynamics. His apparatus, Figure 1.1 was intended to provide known initial conditions for the absorber, known radiation intensity, plane geometry, quasisteady motion, and involve an absorption mechanism of single photon ionization only.

![Figure 1.1 Zuzak's Experiment](image)

Zuzak's experimental goal was unfortunately partially missed since his light pulses were very short, and he had to study dissociation rather than ionization phenomena since his gaseous targets: oxygen and iodine cannot be ionized through any known window material. Zuzak was however able to detect radiation induced pressure pulses in oxygen. In a later attempt Ardila and Cross (2) used a longer light pulse and measured the profiles of the light
induced pressure waves, again using oxygen as target material with dissociating photons as driving energy.

In this thesis the attempt is made to develop the apparatus and design criteria for the study of radiation gas dynamics driven by photoionization fronts in a closed container. The only target materials which can be used for such experiments are alkali metals, and it is the topic of this thesis to report the difficulties encountered in such an attempt.
Chapter 2

INITIAL DESIGN OF THE Cs EXPERIMENT

2.1 An Outline of the Thesis

The presentation of this thesis follows the historical course of the study. In this chapter, some simple and apparently obvious design criteria are derived from the theoretical model of the radiation fronts, which lead us to choose Cs as the working substance and to plan the dimensions and properties of the apparatus.

An important part of the equipment and one that proved to be the most difficult to construct, was the container for Cs absorber gas of high pressure. The trials and errors in the design of this part are discussed in Chapter 3, where we also present measurements of the initial state of the neutral Cs gas and their interpretation.

Experimental observations of photoionization phenomena in the Cs tube and their interpretation are discussed in Chapter 4.

An investigation of the light source is described in Chapter 5.

The main result of this thesis, namely more stringent and more realistic design criteria for such a radiation front study with ionizing photons, is given in the Summary.
2.2 Absorbing Medium

The first requirement of the experiment is the finding of an absorbing medium which can be ionized behind a window, hopefully with radiation which is not absorbed in air, so that readily available quartz windows may be used. The alkali metals turn out to be the most promising candidates, with ionization energies: \( E_{CS} = 3.89 \text{ ev} \), \( E_{Rb} = 4.176 \text{ ev} \) and \( E_{K} = 4.339 \text{ ev} \). We selected Cs because it has the lowest ionization energy (corresponding to a threshold for photo-ionization of \( \lambda = 3185 \text{ Å} \)) and the highest photoionization cross-section, \( \alpha(\lambda) \), (3) (Figure 2.1) of the alkali metals.

![Atomic Absorption Coefficient](image)

**Figure 2.1 Absorption Cross-Section of Cesium**
Since the boiling point of Cs is ≈690°C, it is obvious that to obtain a high absorber density it is necessary to heat the Cs, Figure 2.2.

Figure 2.2 Temperature Dependence of Cs Number Density
The experimental arrangement involved sealing the Cs metal into a glass tube with windows on the ends and placing the tube inside an oven having openings for the ends of the tube. A diagram of the arrangement is shown in Figure 2.3; it shows a light source and the absorption tube mounted inside the oven, whose temperature is variable.

![Diagram of Experimental Arrangement](image)

**Figure 2.3 Diagram of Experimental Arrangement**

### 2.3 Some Properties of Radiation Fronts

In order to determine the dimensions of the absorption tube one has to outline a few basic properties of ideal radiation fronts. Suppose the absorption cross-section for ionizing radiation in Cs is $\alpha \text{cm}^2$. We saw in Figure 2.1 that $\alpha$ varies as function of wavelength, but an approximate average value is $\bar{\alpha} = 1.5 \times 10^{-19}\text{cm}^2$. Then over the distance $L = \frac{1}{N_0 \bar{\alpha}}$, the ionizing radiation will drop in intensity by
about a factor of $e$, see Figure 2.4.

No absorption takes place far to the left of the absorption region, since all the matter there has already been ionized, and hence is "transparent". No absorption takes place yet, in the area far to the right of the absorption front, but if the radiation comes in with constant intensity, the radiation "front", the region where absorption takes place, will eventually reach any point in the neutral region. The radiation front propagates with a velocity 

$$V_F = \frac{F}{N_0} = \text{constant} \times \frac{W}{N_0}$$
F is the photon flux and \( W \) is the radiation energy flux. At this point it is easy to show how dynamical effects can arise in a radiation front. The local energy absorption shown in Figure 2.4 leads to a heating of the absorber, resulting in a temperature distribution as shown in Figure 2.5a. For a steady radiation front the temperature in the hot regime must be high enough to maintain thermal ionization, so that the matter stays transparent to ionizing radiation after the front has passed. The temperature increase leads to a pressure increase of quite similar profile, and a pressure gradient is created, Figure 2.5b.

\[ \rho \frac{dv}{dt} = -\text{grad} \, p, \] is the driving force for the gasdynamical
effects in radiation fronts, namely acceleration and compression of the gas.

The picture outlined here applies to radiation fronts propelled by very intense radiation, for which the front velocity, $V_F$, is faster than the sound speed ahead. For lower intensities, the motion of the radiation front relative to the gas ahead is subsonic, and in this case it is possible that a shock wave will be generated ahead of the radiation front.

2.4 Criteria for Dimensions of the Absorption Experiment

For the design of the absorption tube we use a simple criterion. By assuming that the dynamical effects of radiation fronts become noticeable if the front propagates with a phase velocity, $V_F$, which is at least as fast as the speed of sound in the absorbing medium, $(a = \left(\frac{\gamma kT}{m}\right)^{1/2})$ which is initially estimated as $280$ m/sec, one obtains an upper bound for the absorber density:

$$N_0(T) < \frac{W}{a(T)} = \frac{W_{zuzak}}{280 \text{ m/sec}}$$

This upper density should be attainable with the Cs oven. In a second recursive step one can allow for the temperature dependence of the speed of sound in the neutral absorber and thereby correct for the fact that $N_0$ and $a$ can't be varied independently.
Once the absorber density is determined, the length, $l$ of the total absorption tube is determined by requiring that it should be several times the absorption length $L$, e.g., $l = 4 \times L = \frac{4}{N_o \alpha}$.

Another design criterion which also follows from the absorber density is the radiation pulse duration. If one wants to study steady radiation fronts, the driving intensity should be available for at least a time $t_0$, during which the front propagates through the absorption length $L$; $t_0 = \frac{L}{V_F} = \frac{1}{F \alpha}$, where $F$ is the photon flux. Hence, we see that the parameters are interrelated as shown in Figure 2.6.

![Figure 2.6 Interrelation of Design Parameters](image)

We now turn to the calculation of the parameters of the experiment.

### 2.5 Maximum Absorber Density and Absorber Tube Length

The highest usable oven temperature, dictated by the softening point of quartz tubing, is 800°K. This temperature sets the high limit for $N_o$ in Cs at $1.5 \times 10^{18}$/cm$^3$ (Figure 2.2).
Using the above value of \( N_0 \) and the average value of \( \alpha(\lambda) \) in the region \( 3185 - 2000\AA \), \( 1.5 \times 10^{-19}\text{cm}^2 \), we obtain the minimum radiation front width, \( L = 4.5\text{cm} \). The minimum length of the absorption tube, according to the criterion \( l = 4L \) is then \( 18\text{cm} \). We made \( l = 62\text{cm} \) to enable us to look at fronts with \( L \) up to \( 15\text{cm} \), or \( T = 650^\circ\text{K} \).

2.6 The Light Source

To obtain a front which at \( 650^\circ\text{K} \) would travel through the undisturbed Cs vapor at the sonic speed in the vapor (\( 650^\circ\text{K} \) was chosen rather than the \( 800^\circ\text{K} \) maximum so that a smaller photon flux would be required) one would need a source capable of delivering \( 1.4 \times 10^{22}\text{photons/cm}^2\text{-sec} \) in the range \( 3185 - 1700\AA \) (photons of \( \lambda > 3185\AA \) are no longer able to ionize Cs and \( \lambda = 1700\AA \) is the transmission cut-off of the quartz which will be used for the absorption tube windows).

According to Zuzak, his source, a capillary discharge type commonly called a "Bogen source", at a voltage of \( 3\text{K.V.} \) delivered at a distance of \( 10\text{cm} \) from the source,

\[ 1.16 \times 10^{22}\text{photons/cm}^2\text{-sec} \] in the range \( 1800\AA - 1200\AA \). So that in the range \( 3185\AA - 1700\AA \) the source with the quoted temperature of \( 60,000^\circ\text{K} \), would deliver approximately

\[ 3 \times 10^{22}\text{photons/cm}^2\text{-sec} \]. Furthermore, Zuzak determined that by firing the Bogen source at \( 5\text{KV} \) he could double the output. Therefore by firing the source at \( 5\text{KV} \) it seems that around
6 x 10^{22} \frac{\text{photons}}{\text{cm}^2\text{-sec}} \text{ in the range } 3185\AA - 1700\AA \text{ could be delivered at } 10\text{cm from the source, that is, roughly four times the calculated minimum required photon flux.}

\section*{2.7 Front Velocity and Pulse Duration}

If we assume a photon flux of \(6 \times 10^{22} \frac{\text{photons}}{\text{cm}^2\text{-sec}}\), and a front width of 12cm, corresponding to \(T_{\text{oven}} = 650^\circ\text{K}\), we obtain for the front velocity \(V_F = 10^5\text{cm/sec}\) which corresponds to a flow of Mach 4 in a medium having a speed of sound, \(a = 2.55 \times 10^8\text{cm/sec}\). As was mentioned before, the source must radiate for a time \(t_0 = \frac{L}{V_F}\) if a radiation front is to be formed. For \(L = 12\text{cm}\) and \(V_F = 10^5\text{cm/sec}\), \(t_0 = 120\mu\text{s}\). Actually \(L\) and \(V_F\) are not independent since they are both functions of \(N_0\) and \(t_0\) is only dependent on \(F\) and \(a\).

Our present bank can produce a 90\,\mu\text{s pulse which is essentially flat-topped. The light pulse, which roughly seems to follow the current pulse, is probably not long enough to create a steady front but it should be long enough to study the formation of an ionization front in Cs, especially if one considers that Zuzak was able to observe dissociation front formation in O\(_2\) using light pulses of <10\mu s.
The three main components needed in an experiment to observe the formation of a radiation front are: a source of light; a container for the absorbing medium; and, if the absorber density is controlled by the vapor pressure of Cs, an oven to bring the absorbing medium to the required temperature.

In this chapter, the container for the absorbing medium and the oven are discussed chronologically, that is, the details of their development are described in the order in which they occurred. The source of light will be discussed in Chapter 5.

3.1 Why an Oven is Required

As was mentioned in Chapter 2, to obtain a sufficiently high density of Cs vapor in the absorption tube, it is necessary to heat it. The oven heating the absorption tube sets the temperature distribution for the Cs vessel and in turn determines the number density $N_0$ inside the tube. The distribution of $N_0$ along the tube determines the rate of flow and diffusion velocity of Cs and thus sets the length of time that the Cs in the absorption tube will last. To retard the diffusion flow of Cs to the ends of the tube, inert gas (Helium) is put into the tube at the time that the tube is filled with Cs.
3.2 Design of the Oven

The first oven was constructed from pieces of 1 1/2" thick MARINITE (mainly asbestos fibre) joined together with wood screws (Figure 3.1).

![Diagram of the Oven Shell]

**Figure 3.1 Details of the Oven Shell**

The heating elements were coils of nichrome wire anchored at both ends of the oven on strips of copper which were fastened to the bottom of the oven with wood screws. Three sets of elements (1200W, 600W, 550W) were used. The 1200W element
was used only in the warm up period. When the desired temperature was nearly reached, only the 600W element controlled by a Variac, and the 550W element controlled by a T.C.U. (Temperature Control Unit) were left on. The 600W element was then adjusted with the Variac to reach the desired temperature more closely and the 550W element and T.C.U. then automatically provided the required fine adjustment.

The oven rested on two cylindrical rollers which allowed the oven (with the absorption tube mounted inside) to be moved forward to place the window of the absorption tube as close as possible to the window of the light source. This arrangement also allowed the oven to be moved back so that the light source window could be cleaned (from carbon deposits) after each shot. This oven eventually destroyed itself because the heating elements, when hot, sagged and burned through the bottom of the oven. The second oven which has stood up very well, was constructed in the same way as the first except that the elements were commercial units which have the resistance wire in the grooves of a semi-cylindrical ceramic base. Three of these heating units, each with a power capacity of 550W were mounted in line in the oven and were connected so that the two outer units were controlled by a Variac, while the central unit was connected to the T.C.U. Two probes were placed in the oven during normal operation: the sensor of the T.C.U. and
a chromel-alumel thermocouple. The two probes were positioned at approximately the center of the oven, where the maximum temperature was expected, so that the maximum temperature would be monitored continuously. The fastest and most convenient way to operate the oven was to turn on all three heating elements to their maximum capacity until the temperature was near the desired temperature and then to shut off the two end elements, leaving only the central element controlled by the T.C.U. The temperature would initially oscillate and then settle down to steady

![Figure 3.2 Temperature Distribution in Oven When Heating With the Center Element Only](image-url)
values with a rather uneven temperature distribution as shown in Figure 3.2.

When a more even temperature distribution was desired, the Variac controlling the two outside elements was adjusted until a temperature slightly below the desired value was reached. The central element controlled by the T.C.U. was then switched on in addition to provide the fine adjustment. Figure 3.3 shows the distribution of the temperature in the oven using the second procedure.

![Figure 3.3 Temperature Distribution in the Oven, Heating With All Three Elements]
It has been suggested (4) that one way of obtaining a very even temperature distribution in the Cs tube is to convert the tube into a heat pipe. This could be accomplished by inserting stainless steel wire mesh inside the tube so that the walls of the tube and the wire mesh are in contact. The wire mesh in contact with the inside wall of the tube would, by capillary action, be able to keep the tube well supplied with molten Cs, satisfying the requirement for a heat pipe. However, as attractive as is the idea of a heat pipe Cs tube, it would, in practice, be very difficult to construct except, perhaps, for a perfectly cylindrical tube, because of the difficulty of placing the wire mesh in close contact with the inside wall of the tube. For that reason, the heat pipe Cs tube was not built at this time.

3.3 Designs of the Absorption Tube

The basic requirements of the absorption tube are firstly to contain Cs vapor of \( N = 10^{18} \text{ particles/cm}^3 \), which requires ambient temperatures of \( \sim 800^\circ \text{K} \). Secondly, a window (quartz) has to be provided so that Cs vapor can be exposed to ionizing radiation. Thirdly, it was considered advisable to have electrical wire probes protruding into the Cs vapor to carry out conductivity measurements. At the beginning of the work it was thought
that these requirements could be met with the design shown in Figure 3.4.

![Figure 3.4 Initial Design of Absorption Tube](image)

Basically this absorption vessel consisted of a quartz tube with quartz windows fused onto the ends which was evacuated and filled with Cs metal. The tube was of the same length as the outside dimensions of the first oven (100 cm) so that the ends of the tube, which were sitting in the slots in the oven were flush with the outside of the oven. No supports were provided for the tube other than at the ends where the tube rested in the oven slots. The only other significant feature of that first tube was, three sets of tungsten electrodes (see Figure 3.4) which were to be used to detect electrical conductivity changes in the Cs vapor due to photoionization of the vapor. The tube proved to be unsuccessful because Cs vapor condensed on the quartz windows making them opaque to light from the
Bogen source. In addition, the hot Cs vapor destroyed the tungsten electrodes and seemed to attack the walls of the quartz tube.

The second absorption tube was made longer than the outside of the oven (the second oven), so that cooling "collars" could be placed around the ends of the absorption tube which now protruded from the oven. The cooling "collars" (made from strips of copper braid, one end of which was wound around the absorption tube and fastened in place and the other end placed in a dewar of liquid Nitrogen) were meant to cool the ends of the absorption tube so that the Cs vapor could condense on the walls of the tube before reaching the quartz windows. To retard the flow of Cs vapor to the cold ends, the tube was filled with Helium gas (p=160 torr). This Helium gas was drawn from a "reservoir", connected as in Figure 3.5, to keep the total pressure at any point in the absorption tube roughly the same.

As a further change, no wire electrodes were fused into the tube, but instead small depressions were provided in the quartz wall of the tube so that small capacitive probes could be attached there. The pyrex tubing connection between the absorption tube and the He reservoir proved to be quite fragile, and after it broke, the tube was modified by changing the location of the reservoir, as in Figure 3.6, to make it more sturdy.
The basic operation of the tube was found to be satisfactory since no deposit of Cs could be noticed on the windows of the tube and transfer of Cs from the central reservoir to the ends of the tube was sufficiently slow that it was possible to run the tube for a couple of hours before
the one gram of Cs in the reservoir was transferred to the ends. Eventually the cooling "collars" were discarded when it was found that even without them, all the Cs seemed to condense in the first 4 cm past the oven wall.

Since interpretation of electrical probe signals to obtain quantitative data is, in most cases, quite difficult, the principal means of detecting the photoionization front was to be the observation of CsI lines which would appear when the Cs, ionized by the front, recombined.

The initial attempt to observe CsI lines by looking at the side of the absorption tube through a hole in the oven wall (using a monochromator (M.C.) with a photomultiplier (P.M.) mounted on the exit slit) revealed that the walls of the absorption tube were opaque, probably due to a film of liquid Cs coating the inside wall of the tube. To allow light from inside the absorption tube to be detected, the tube was changed by the addition of four side tubes with quartz windows fused on the ends (Figure 3.7). The side tubes were surrounded by auxiliary heating coils which made the side tubes "hot spots" where Cs would not condense. Although one pair of side tubes on one side would seem superfluous, the tubes are necessary to prevent reflections from the tube wall (of the light from the Bogen source) from entering the monochromator. The purpose of having two places at which the absorption tube could be observed was to allow measurement of the front velocity from the
Figure 3.7 Final Configuration of Absorption Tube and Light Detecting Arrangement
delay in the arrival of the signal between the two ports. In addition, with the two port system, the development of the front could be deduced from the shape of the signals at the two ports. In order that the signals from the two ports could be studied simultaneously, using the one available monochromator, and to prevent spoiling the alignment between the monochromator and the side ports each time the oven was moved (to allow the window of the light source to be cleaned) each side tube was optically coupled to the entrance slit of the M.C. (Jarell Ash 1/2m) by a fiberoptics cable, as shown in Figure 3.7. At the oven, a holder, screwed onto the oven wall, positioned each fiberoptics cable exactly opposite a side port of the absorption tube. A suitable clamp held both fiberoptics cables in place in front of the M.C. entrance slit. This arrangement eliminated optical adjustment problems. The sum of the light signals passing through the M.C. exit slit was transformed into an electrical signal by an R.C.A. IP21 photomultiplier and displayed with a 555 Tektronix oscilloscope.

Since no signal could be obtained, it was obvious that in spite of the auxiliary heaters, Cs had coated the side tube windows. Therefore, in the final design, as shown in Figure 3.7, the side tubes were extended so as to protrude from the oven in order that Cs would condense on the walls of the side tubes before reaching the windows.
3.4 Cesium Recirculation

The last two tubes were used for longer periods of time than earlier models, so that the problem arose as to how to return the Cs that had condensed at the ends back to the middle of the tube, once the reservoir in the middle of the tube was depleted of Cs.

One way of returning the Cs to the middle of the tube would be to heat the ends of the tube (using heating tapes, for example) and cool the middle, reversing the temperature gradient which had brought the Cs to the ends. This method was discarded because it was slow and would endanger the end windows which would be exposed to the hot Cs vapor.

We then resorted to using gravity to return the Cs to the middle of the tube. The procedure was to allow enough Cs to accumulate at the ends, take the tube out of the oven, cool one end of the tube to solidify the Cs accumulated there, then tip the cold end down, allowing drops of Cs at the uncooled end to slide down into the reservoir in the middle. Similarly, the Cs was coaxed from the other end of the tube back into the middle.

The above method allowed some Cs from the ends to be brought back to the middle so that the tube did not have to be refilled with Cs each time that the reservoir was empty. However, this method is not entirely successful because much of the Cs adhered to the tube wall (some reacted with the quartz) and could not be coaxed to the
reservoir. As a consequence, after the Cs had been returned to the middle, two or three times, there wasn't enough Cs at the ends to form a drop that could be returned to the middle.

3.5 Density Distribution in the Absorption Tube

For absorption measurements, one has to know the density distribution of Cs atoms inside the tube. The distribution may be obtained as follows (5). We start with the tube cold and the inert gas present at a certain pressure \( P_i \). Let us assume that the tube is connected to a reservoir of large volume so that subsequent changes in the temperature of the absorption tube do not alter the pressure in the reservoir very much. Then the total pressure at any point in the absorption tube will always be \( P_t \). As the Cs is heated, the partial pressure of the vapor, \( P_c \), at any point in the absorption tube will increase and that of the inert gas, \( P_i \), will decrease so as to keep their sum equal to \( P_t \). Thus the vapor drives out part of the inert gas, and when a steady temperature is reached, the vapor-gas mixture is in a state of dynamic equilibrium. There is no net movement of the inert gas in any direction, but there is a slow transfer of the Cs by diffusion of the vapor (driven by the gradient of the cesium pressure, \( \text{grad } P_c \)) through the inert gas. This type of equilibrium remains only so long as the vapor pressure is less than \( P_i \). If the vapor pressure exceeds \( P_i \),
convection of the vapor (as opposed to diffusion) takes place and the metal is very rapidly transferred to the ends of the tube. If a vapor pressure of the order of $0.8 P_f$ is used (5), the rate of diffusion of the vapor is still slow and the partial pressure of the inert gas in the main portion of the absorption tube is considerably less that that of the vapor.

The usual theory (6) for the one-dimensional problem of inter-diffusion of two gases in a tube of uniform bore leads to the relations for mass flux $\Gamma$, (3.1)

$$\Gamma_1 = -D \frac{dn_1}{dx}, \quad \Gamma_2 = -D \frac{dn_2}{dx}, \quad \Gamma_1 = \Gamma_2$$

where $n_1$ and $n_2$ are the concentrations of the vapor and gas respectively at the point $x$; $\Gamma_1, \Gamma_2$ are the numbers crossing a unit area from left to right, at the point $x$, per second and $D$, is the diffusion coefficient. In the usual problem to which equations (3.1) apply, both gases move along their own concentration gradients and $n_1$ and $n_2$ are functions of time. In our problem, which is similar to that of Ditchburn (5), the vapor diffuses through the inert gas and there is no net motion of the latter. To take into account this effect, we assume that at any point there is a movement of the whole system considered above, sufficient to transfer $\Gamma_2$ molecules of the inert gas from
right to left. This will also transfer \( \frac{n_1}{n_2} \) \( \Gamma_2 \) molecules of the vapor from right to left or \( -\frac{n_1}{n_2} \) \( \Gamma_1 \), from left to right, so that the total movement of the vapor component is:

\[
(3.2) \quad \Gamma^* = -(\frac{n_1}{n_2} + 1)\Gamma_1 = (\frac{n_1}{n_2} + 1)D \frac{dn_1}{dx}
\]

After dynamic equilibrium is reached, the density of Cs vapor at each point in the tube is nearly the saturated vapor density at that point, and the flow of Cs vapor is determined, at each point, by the local particle density.

Since diffusion of Cs molecules certainly takes place in the Cs tube heated up in the oven, it is important to know whether this motion is significant when studying the dynamics of radiation fronts in Cs vapor. For instance, if the bulk velocity of Cs, due to diffusion, were equal and opposite to the propagation velocity of a radiation front, such a radiation front would not move at all in the lab frame of reference.

The diffusion velocity can be obtained from the diffusion flux \( \Gamma^* : V_\Gamma = \frac{\Gamma^*}{n_1} \) where the diffusion flux can be obtained approximately assuming that the density distribution \( n_1(x) \) is solely determined by the temperature distribution (Figure 3.2) and the vapor pressure curve of Cs (Figure 2.2). By this method the local diffusion velocity
$V_T$ was calculated. The numerical result is displayed in Figure 3.8.

![Graph of Cs Vapor Diffusion Velocity vs Distance Along Absorption Tube](image)

Figure 3.8 Cs Vapor Diffusion Velocity vs Distance Along Absorption Tube

It is seen that $V_T$ is very small indeed, and small compared to the speed of sound in the Cs gas, $a$. Therefore, we firstly conclude that the density distribution is not significantly changed from the "static" value, which we used to calculate $V_T$. This density distribution is shown in Figure 3.9. Secondly, we see that this small bulk motion
is completely negligible when interpreting any radiation
gasdynamical velocity measurements, since velocities of the
order of 0.1 m/sec can certainly not be measured with any
available method.

![Graph showing Cs Vapor Number Density vs Distance Along Absorption Tube]

Figure 3.9 Cs Vapor Number Density vs Distance Along Absorption Tube
3.6 Maximum Temperature Gradients

It is, at this stage, informative to know how large a temperature gradient, and hence resulting density gradient, could be sustained before the diffusion velocity would become so large that it changed the density distribution appreciably and would affect the interpretation of front velocities in Cs.

The size of the temperature gradient \( \left( \frac{dT}{dX} \right)_{\text{max}} \) which will lead to a non-negligible flow velocity, can be calculated if one chooses a maximum tolerable velocity.

![Figure 3.10 Maximum Tolerable Temperature Gradient as a Function of Temperature](image-url)
For the present calculations, the maximum tolerable velocity, \((V_p)_{\text{max}}\), was chosen equal to \(\frac{a}{10}\), (where \(a\) is the speed of sound) for which the plot is shown in Figure 3.10.

The results of Figure 3.10 can, for instance be used to estimate how fast the temperature may drop off without having to worry about diffusion. As an example take two points A and B, point A being at a temperature \(T_A = 720^\circ\text{K}\) and B at \(T_B = 400^\circ\text{K}\). Using the minimum temperature gradient on Figure 3.10 between A and B,

\[6 \times 10^3 \frac{\text{°K}}{\text{cm}}\]

it may be seen that the two points can be as close together as:

\[
\Delta x = \frac{dx}{dT} \Delta T = \frac{320^\circ\text{K}}{6 \times 10^3 \frac{\text{°K}}{\text{cm}}} = 0.05 \text{ cm}.
\]

This distance is so small that one can safely assume that in any oven configuration in which the Cs is heated from outside, diffusion effects can be neglected when studying macroscopic gasdynamical phenomena.

It appeared then that the absorbing medium fulfilled all requirements for radiation front experiments. We therefore proceeded with the study assuming that the light source behaved as described by Zuzak.
EXPERIMENTAL RESULTS

With most of the problems of making a Cs absorption tube overcome, detection of the de-exitation signal from Cs, indicating the presence of a radiation front, was attempted. A description of the experimental arrangement, which will be outlined briefly here, was given in detail in Chapter 3 (diagram on Figure 3.5).

4.1 Apparatus for the Optical Measurements

The apparatus used to measure the photoionization in the Cs absorption tube consisted of two fiberoptic cables attached to observation ports on the Cs tube; the cables were connected to the entrance slit of a single photomultiplier whose output was fed into an oscilloscope. When the oven was heated to the required temperature (650°K), the capacitor bank (charged to 8-10KV) was triggered and the oscillogram of the sum of the two light pulses (from the two fiberoptic cables) was taken.

4.2 Search for a Front Signal- Optical Method

The sum of the two observation port signals unfortunately did not differ in shape from the signal coming from either one of the two ports alone, indicating that either there was no radiation front produced in the Cs vapor or that the front velocity was very large resulting in the almost simultaneous arrival of the front at the two observation
ports or that most of the detected light was not coming from an ionization front at all, but rather was stray light from reflections of the Bogen light pulse from the absorption tube and from the internal surfaces of the oven. Unfortunately, however, we were unable to determine the origin of the optical signals, so that these observations were abandoned without conclusions.

In order to avoid problems relating to the detection of light signals buried in a background of stray light, an attempt was made to detect the front or any net photoionization in the Cs vapor by means of electrical probes.

4.3 Electrical Probes

With the electrical probes, the contention was that if the photoionization proceeds in a radiation front, there should be a delay in signal between the probes positioned along the absorption tube. The probes were capacitive probes of the type investigated by Whelan (7), and consisted of single turns of bare 28 gauge nichrome wire wrapped around the absorption tube at three different points, as shown in Figure 4.1. The probes, terminated with 50Ω to ensure a fast rise time were connected to a dual beam Tektronix 555 scope with two 1A1 dual trace plug-ins so that four signals could be recorded simultaneously, the three from the probes and the bank current. In addition, the signals
from any two probes could be combined to give the sum or difference signal.

Figure 4.1 Location of Electrical Probes

At the start, the oven was heated and a few shots were taken with the light from the Bogen source (using discharge voltages of 8-10KV) blocked off from the absorption tube to check on the total electrical noise. The oscillograms from those first shots (Figure 4.2) show that the electrical noise induced in the probes is smaller than 10 mV peak to peak except for the first 3μs where the noise can rise to approximately 20 mV p.p.

Next, the obstacle between the Bogen source and the Cs tube was removed to allow the light pulses to reach the Cs vapor. Oscillograms taken under those conditions (and using oscilloscope sweep speeds of 2-10μs/cm) showed signals from all three probes (Figure 4.3) which are clearly caused by the light pulse.
Unfortunately, the probe signals were not reproducible and resisted many attempts to make them reproducible. Furthermore, there was no indication that any delay in the rise of the probe signals 1, 2, 3 could be detected.

4.4 Analysis of Probe Signals Observed on a Long Time Scale

Following the attempts described above, detection of signals from the probes at a long oscilloscope sweep speed (1ms/cm) was tried. As before, oscillograms were obtained with the light from the source obstructed to check on the electrical noise picked up by the probes. Except for a very small disturbance right at the origin, the traces were completely flat indicating that noise pickup would not be a problem.

When the light from the source was allowed to reach the Cs vapor, signals were obtained from all three probes (Figure 4.4). These signals showed little, if any, variation from shot to shot.
Figure 4.4 Electrical Probe Signals - Slow Sweep Speed

The interpretation of the signals from the probes is that they are due to photoionization, and represent the charge on the absorption tube wall at the location of the probe. The charge on the tube wall, which according to the interpretation of the signals, rises quickly (<5μs) and decays rather slowly (.43-3.55 ms) is due to separation of electrons and Cs ions which results from their greatly different mobilities. The situation seems to be that after the Cs has been ionized by the radiation, electrons arrive very quickly to the relatively cold walls of the tube, followed by the much slower Cs ions which then neutralize the charge.

Essentially, two sets of measurements may be obtained from the traces of Figure 4.4: the maximal signal values and the signal decay times for the three probes. In addition, it is possible to get an indication of signal rise times, but these are more easily obtained from oscillograms taken at shorter sweep speeds. Comparison of the rise and decay times of the signals shows their ratio to be approximately the same as the ratio of the mobilities of an electron.
and a Cs ion, which gives weight to the interpretation that there is charge separation. Furthermore, plots of the signal value vs time on semilogarithmic paper, Figure 4.5, show that the decay is exponential, indicating that the decay process is diffusion and/or electron attachment (8).

![Graph showing signal value vs time for three probes.](image)

**Figure 4.5 Signal Value vs Time for the Three Probes**

Electron attachment is strongest to those atoms which have their outer electronic shells nearly filled; there is no attachment to the Helium buffer gas and the attachment to Cs atoms, to form Cs⁻, is very weak (9), so that ambipolar diffusion becomes the most probable process in the probe measurements. Attempts to relate the probe signal decay times and maximum values to the electron density were not fruitful, due mainly to the complex geometry of the absorption tube.
The probe measurements showed that although photoionization of Cs vapor was taking place, the rate of ionization and hence the intensity of the light source was not sufficient to create a front.

From the calculations of Chapter 2, where certain assumptions about the light source were made, it appeared that the intensity and duration of the light pulse from the Bogen source would be sufficient. Therefore, at this time, it was decided to investigate the source to check whether its characteristics matched the assumptions that were made about it on the basis of Zuzak's and Cross's work. The investigation of the light source is the subject of Chapter 5.
5.1. Requirements for the Source

In Chapter 2 it was mentioned that to obtain a radiation front which at 650°K would travel through Cs vapor at the sound speed, a source was needed which could supply \(1.4 \times 10^{22}\) photons/cm\(^2\)-sec in the range 1700Å - 3185Å, 10 cm from the source, for 120\(\mu\)s. Since it would be desirable to drive the front faster than at the sound speed, the figure

\[1.4 \times 10^{22}\ \text{photons/cm}^2\cdot\text{sec (1700Å }<\lambda< 3185\text{Å)}\] for 120\(\mu\)s, is really the minimum that the required source should deliver to the Cs vapor contained in the absorption tube.

The ideal source would be able to supply much more than \(1.4 \times 10^{22}\) photons/cm\(^2\)-sec continuously. Such a source is not available and even if it were, it would require an impractically large power supply (\(\approx 100\) MegaWatt). Thus the only possible sources for the experiment are pulsed sources. Probably the most common pulsed sources are arc discharges. There, a charged capacitor or bank of capacitors discharges through an insulator (usually a gas) ionizing it and creating a luminous plasma.

5.2 Constricted Arc

One type of arc discharge, the design of which has been optimized by P. Bogen et al (10), for the production of light
is a capillary arc. Our version of the capillary arc is shown in Figure 5.1.

![Figure 5.1 The Bogen Light Source](image)

Basically the "Bogen" source produces a high current discharge in a narrow channel drilled through a polyethylene, or similar insulating material rod. The discharge, squeezed through the hole, vaporizes the polyethylene at the walls and produces an extremely hot high density plasma which radiates along the axis of the hole. Unfortunately, much of the polyethylene plasma consists of vaporized carbon which squeezes out of the ends and tends to coat the window of the source with an opaque layer, requiring that the window be cleaned after each shot.

The usual firing procedure was as follows. The system was pumped down to below 20µHg, which was sufficiently
low to ensure that breakdown did not occur. The condenser bank, described below, was charged to the desired value (usually from 3 to 10KV). The light source was fired by allowing Argon into the system by way of a selenoid actuated valve. This raised the pressure in the system until, for the applied voltage, a point on the Paschen curve was reached where breakdown occurred. After the breakdown, the system was brought to atmospheric pressure so that the window holder (designed for easy removal) could be taken off and the window cleaned of the coating carbon. The window holder having been returned to its place, the system was once again pumped down in preparation for another shot. Before each shot the Cs absorption tube, in its moveable oven, was placed as close as possible to the light source, to obtain the highest possible intensity. After the shot the oven was pulled back so that the Bogen source window could be removed, cleaned and replaced. The entire firing cycle took from 2 - 10 minutes depending on the condition of the vacuum pump and the agility of the operator on that day.

Initially, the light source was triggered electrically, by applying a pulse of ≈16KV which started breakdown in an external spark gap in series with the source. However, it was found that the large amount of electrical noise generated in connection with the trigger pulse was unacceptable for some of the investigations which were performed, and so this method was eventually abandoned.
The design of the electrodes and the spark channel which is illustrated in Figure 5.2 was based on the source described by Zuzak (1). It consists of two brass electrodes cast in epoxy (strengthened with fiberglass tape) which also separates the electrodes. A 3/4" diameter threaded polyethylene rod is screwed into the epoxy such that the 3 - 4 mm diameter hole in the rod serves as the axis of the cylindrically symmetric apparatus.

The dump chambers (Figure 5.1) consisting of 2" I.D. Pyrex tube (3" long in the front, 12" in the back) were sealed to the light source with rubber gaskets. The windows were 1/8" thick, 1" diameter optical flats of quartz, U.V. sapphire or LiF. LiF windows have the best transmission characteristics, passing =50% of the light at 1200Å as compared to 50% at 1900Å for sapphire (Al₂O₃) and 50% at from 1700Å - 2200Å for different grades of quartz. However, quartz windows seemed to be the best in withstanding the combined thermal and mechanical shocks resulting from the firing of the source, with LiF and sapphire windows being roughly the same and poorer than quartz. At a discharge voltage of 9KV or greater none of the windows lasted for more than two shots before they became "frosted", at which point their transmission dropped to a fraction of their "undamaged value". Although damage to the windows could be avoided, either by keeping the discharge voltage sufficiently low or by moving the window away from the source, it was
Figure 5.2  Cross-Sectional View of Bogen Source
found that a good tradeoff was achieved if the window was kept as close as possible to the discharge and the voltage kept below 8KV.

5.3 The Power Supply

To simulate a direct current of large magnitude (thus avoiding time-dependent phenomena associated with a time varying current) a power supply is required which can provide a square current pulse. To obtain square current pulses in the kiloamp range, a lumped transmission line, Figure 5.3, was used.

![Diagram of N-Section Lumped Transmission Line]

\[ n=5 \quad C_{i=5}=10\mu F \quad R=1\Omega \]

\[ L_{i=4}=4\mu H \]

**Figure 5.3 N-Section Lumped Transmission Line**

The length of the square current pulse is given by

\[ T = 2N\sqrt{LC} \]

and the current \( i \) in the pulse is roughly
given by $\frac{V}{2R}$. The power supply used for the Bogen source consisted of five $10\mu F$ capacitors connected with inductances of $\approx 4\mu H$ and gave a pulse which was $90\mu sec$ long with a top that was essentially flat for $\approx 50\mu s$ (see Figure 5.4).

![Figure 5.4 Current Pulse from Lumped Transmission Line](image1)

![Figure 5.5 Light Pulse from Bogen Source (Taken at 7KV)](image2)

Figure 5.5 shows a typical trace of photomultiplier output vs time for a light pulse from the Bogen source, using the power supply described above. As may be seen by comparing Figure 5.4 and Figure 5.5, the general shape of the light pulse follows closely that of the current pulse.

5.4 Light Intensity vs Discharge Voltage

Traces like the one in Figure 5.5 were obtained for different values of the discharge voltage. From these traces, a graph was constructed of the peak photomultiplier output vs discharge voltage. Since the duration of the light pulse is constant, and the intensity is practically constant for
all voltages, the graph of peak light intensity vs discharge voltage in the investigated range 1-10KV, Figure 5.6 will be almost identical to a graph of integrated pulse intensity vs. discharge voltage.

![Graph of peak Bogen Source Output vs Discharge Voltage](image)

**Figure 5.6 Peak Bogen Source Output vs Discharge Voltage**

A graph of log intensity vs log discharge voltage is shown in Figure 5.7. On the same axes is plotted log (discharge voltage)\(^2\) [proportional to the energy stored in the capacitor bank] vs log discharge voltage.
From Figure 5.7, it is apparent that the intensity from the Bogen source increases as the energy in the discharge except for a "kink" between 2 and 3KV, most likely due to "frosting" of the source window at voltages greater than ~2KV. This "frosting" appears to be due to a combination of thermal shock which creates a surface fracture pattern and pitting of the surface from the impact of carbon particles emitted from the source. The curve of intensity vs discharge voltage shown in Figure 5.6 is essentially similar to that obtained by Zuzak, the only difference being that, in Zuzak's
case, the kink due to window damage occurs at ≈5KV rather than at 2KV. The shorter light pulse (≈6μs) used by Zuzak is apparently not as damaging to the window as the longer (≈90μs) pulse used for this experiment.

5.5 Relative End-On Spatial Intensity Distribution

To obtain the spatial distribution of intensity for the Bogen source, photographs were obtained using the arrangement shown in Figure 5.8.

35mm camera  

frosted screen  

s  

bogen source  

Figure 5.8 Arrangement for Obtaining the Relative End-On Spatial Intensity Distribution of the Bogen Source

Photographs were taken at two screen to source distances, s, the longer distance corresponding to the position in the absorption tube at which the Cs vapor density became significant. In addition, photographs were taken of an evenly lighted step-wedge and were used to construct the H & D curve for the
film (Panatomic X). From densitometer measurements of the photographs and the H & D curve, intensity plots were obtained for the two distances s, as shown in Figure 5.9.

These plots yielded the spreading of the beam with distance, which was used to determine that the constricted arc radiates like a point source located inside the capillary
channel of the Bogen, 2.5 cm from the end of the capillary. The ratio of the intensities at the two screen positions differs by a factor of two from what is expected by considering the ratio of the source to screen distances. The discrepancy, however, can be accounted for by observed shot to shot differences and slight differences in the discharge voltages.

5.6 Absolute Intensity Measurements

The absolute intensity of the Bogen discharge was measured at the source window by comparison with the intensity of a standard carbon arc. Care was taken that the optical arrangements were the same for the two sources. The experimental set up is shown in Figure 5.10.

![Figure 5.10 Equipment Used for Absolute Intensity Measurement of Bogen Source](image-url)
The quartz lens was used to magnify the image of the source so that the brightest central 2 mm of the source covered the entire length of the monochromator slit.

First, the output of the carbon arc (which was run as prescribed by Null and Lozier (1962) (11) was measured as a function of wavelength in the range 3150Å - 2000Å (see Figure 5.11). A chopping wheel was used between the carbon arc and the monochromator to avoid the difficulties associated with D.C. measurements. Next, using the identical optical arrangement, but without the chopping wheel, oscillograms were obtained for the Bogen source at different wavelengths between 3100Å and 2000Å, using a discharge voltage of 3KV. Neutral density filters (aluminized quartz optical flats) of known transmission characteristics in the U.V. were used between the Bogen source and the monochromator to prevent saturation of the photomultiplier and to keep the P.M. output in the same range as the output for the carbon arc. From the oscillograms, the curve of peak P.M. output (adjusted by the attenuation factor of the neutral density filters) vs wavelength was constructed; it is shown in Figure 5.11 which, in addition shows the ratio of adjusted Bogen source P.M. output over carbon arc P.M. output for the range 3100Å - 2000Å.
Figure 5.11 Comparison of Bogen Source and Carbon Arc Outputs
The emissive power of the standard carbon arc at different wavelengths may be calculated from Planck's Radiation formula \( E_\lambda = C_1 \lambda^{-5} \exp(-C_2 \lambda^{-1}T^{-1}) - 1 \); then using the B.S. C.A. ratio curve (Figure 5.11), the emissive power of the Bogen source window is obtained (Figure 5.12).

![Graph](image)

**Figure 5.12 Emissive Power of Bogen Source**
Integrating the curve of Figure 5.12, the value of \( \frac{367}{\text{cm}^2} \) is obtained for the peak intensity in the range \( 3150\text{Å} - 2200\text{Å} \). Since the light emitting area of the Bogen source window is approximately \( 2.4 \text{ cm}^2 \), then through the window the peak power (Bank Voltage = 3K.V.;

\( 3150\text{Å} > \lambda > 2200\text{Å} \)) is 882 watts and the energy per pulse is 56 millijoules. From Figure 5.12 one can also establish the peak photon flux through the source window under the same conditions; that turns out to be \( 5.4 \times 10^{20} \) photons/cm\(^2\)-sec. This value is unfortunately a factor of 25 below the minimum photon flux wanted for the radiation front experiment.

5.7 Source Temperature

Referring the integrated peak radiation intensity (367 W/cm\(^2\)) to the capillary exit (.15cm\(^2\), 10 cm from the window) of the Bogen source, one obtains the value 1.5 Megawatt/cm\(^2\) for the radiation intensity. This figure for the peak intensity is an effective value along the axis of the Bogen source; it implies that, on axis, the Bogen source is equivalent to a black body source which radiates 1.5 M.watt/cm\(^2\) into a half-sphere. Figure 5.13 shows an attempt to assign a black body temperature to the source.
Figure 5.13 Emissivity of Bogen Source and Black Body Emissivity Curves

Since the Bogen emissivity curve cuts across the emissivity curves of sources from 10,000°K to 170,000°K, it is apparent that a characteristic temperature cannot be ascribed to the source. However, the range, 10,000°K to 170,000°K includes the temperature of 60,000°K assigned
by Zuzak to the Bogen source with a short (≈6μs) discharge.

The peak radiation intensity is dependent not so much on the length of the current pulse as on its risetime: the faster the risetime the greater the peak intensity. The lower radiation intensity produced by a slowly rising current pulse may be explained if one examines conditions in the source channel. A slowly rising current pulse allows a considerable amount of the hot plasma in the channel to escape during the current pulse, reducing the pressure in the channel. If the radiation is not black, a lower pressure in the channel will produce a lower peak radiation intensity than if the current pulse is fast where inertia prevents the gas from escaping out of the ends. In some cases, the length of the current pulse may be important. For a long pulse, the ejected plasma cools and becomes a radiation absorbing cloud which attenuates the radiation. This contention is in agreement with Cross's observations of the discharge plasma hydrogen and carbon escaping out of the ends of the capillary.
Chapter 6

SUMMARY AND POSSIBLE IMPROVEMENTS

6.1 Summary

For the study of steady ionization fronts one needs an intense light source and a sufficiently high absorber number density. In this study, design criteria for such an experiment were developed and some of the ideas experimentally tested. The absorbing medium, Cs gas, can be heated up to a maximum of about \( T = 800^\circ \text{K} \) so that an absorber density of \( N_0 = 1.5 \times 10^{18} / \text{cm}^3 \) can be reached. This leads to an absorption length, for ionizing radiation, of 
\[
L = \frac{1}{N_0 \alpha} = 4.5 \text{ cm.}
\]
The length of the absorption tube was chosen to be 62 cm., which is large compared with the absorption length \( L \). The intensity \( W = h \nu F \) of the ionizing radiation should be so high that the radiation front velocity \( V_F = \frac{F}{N_0} \) is comparable with the speed of sound in the absorber gas. This criterion leads to a minimum photon flux, 
\[
F_{\text{min}} = 1.4 \times 10^{22} \text{phot-cm}^{-2} \text{sec}^{-1},
\]
which should last for the time 
\[
t_o = \frac{L}{V_F} = 120 \mu \text{s},
\]
within which the front would sweep through the absorption tube.

An absorption tube and an oven for the tube were designed according to the above criteria and were subsequently built and tested. A constricted arc light source was constructed which was believed capable of delivering the required intensity (1) and time duration.
The number density of Cs vapour, \( N_0 \), in the absorption tube was determined from measurements of the temperature along the tube, and from the distribution of \( N_0 \), it was established that the convection flow of Cs in the absorption tube was small and that the Cs flow velocity, \( V_f \), was negligible compared to the expected radiation front velocities.

Attempts to measure the radiation front velocity from the delay in the optical signal at two observation ports on the absorption tube proved to be inconclusive due to stray light problems. Electrical probe measurements taken at three points on the absorption tube showed that radiation induced ionization of the Cs vapour was taking place, but that the rate of ionization was not sufficiently high to produce a front. This raised the suspicion that the light source was less intense than was expected.

A subsequent investigation of the characteristics of the Bogen light source used for this experiment showed that the output of radiation capable of ionizing Cs was, at the position of the dense Cs absorber, a factor of 25 too low to produce a front under the present arrangement of the experiment. Since the light intensity from the source drops quickly as one moves farther from it, it appears that radiation fronts cannot be produced with the present source unless the test section of the absorption tube and the source can be located closer together without
exposing the window of the absorption tube to the corrosive action of the hot Cs vapor.

6.2 Possible Improvements

In the experiment to study ionization fronts in Cs vapor, several areas can be discerned where improvements possibly could be made.

The greatest shortcoming of the experiment proved to be an inadequate source of light. The shortage of ionizing photons could, at least partially, be overcome if one were to place the source much closer to the active (high $N_0$) region of the absorption tube. That can be accomplished in one of two ways: either one cools strongly the absorption tube at the position where it emerges from the oven so that a long length of tube becomes unnecessary (to prevent damage to the windows) and the tube's active region can be placed very close to the light source, or another way would be to enclose in an oven the absorption tube and part or all of the light source, again minimizing the distance between source and absorption tube. A third method of increasing the number of photons reaching the absorption tube is to produce more in the first place. This could be accomplished by upgrading the power supply of the light source. If the capacitance of the discharge bank is increased, then the value of the required
load resistor would drop and the peak discharge current as well as the light intensity (which depends on the discharge current) would increase.

To obtain a measurable delay between the signals at the electrical probes or observation ports on the absorption tube, a radiation front can be slowed down by increasing the absorber density, $N_o$. Raising $N_o$ then has the added advantage that the absorption length $L$ decreases so that the length, $l$, of the absorption tube can be made smaller, making the apparatus more compact. Using the quartz absorption tube, the maximum oven temperature is 800°K which is the softening point of quartz. To obtain the higher Cs densities that are possible only if the absorption tube is heated to temperatures in excess of 800°K, a material other than quartz must be employed. Stainless steel of a type that could withstand the corrosive properties of Cs vapor, would be a suitable material for the body of the absorption tube while U.V. grade sapphire could be used for the windows if these were subjected to high temperatures.

An area of the experiment where improvements would be welcome is the window of the source. As matters stand, the source window must be cleaned after every shot and must be replaced periodically when cumulative damage to the window (from the capillary discharge) becomes severe. A method is required which will remove the need to clean the window after each shot as well as prevent the destruction
of expensive optical flats. Such a method has not, to this time been found.
BIBLIOGRAPHY


(4) J. Cooper, Private Communication.


