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A hollow cathode source for spectroscopic investigations.

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Boston University
A HOLLOW CATHODE SOURCE FOR SPECTROSCOPIC INVESTIGATIONS

by

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Introduction

During recent years the interests of experimental spectroscopists have changed from the development of high resolution instruments to the development of light sources. One of the most promising types of light sources is the hollow cathode glow discharge tube. Discovered by F. Paschen in 1916, this type of tube has been modified and improved to provide important information regarding the hyperfine structure of atomic nuclei. It can be operated with either large or extremely small quantities of a material. This type of source can produce bright sharp lines and at the same time can be very economical in its use of the material under investigation.

The design of the tube can be modified as was originally done by H. Schuler (1) to provide for cooling of the cathode, thereby reducing the spreading due to the Doppler effect. The spreading due to the Stark effect is also reduced since the glow is located in a space having a very small electrical field.

An exciting gas, pumped through the tube is used to decrease the rate of diffusion of the material under investigation. This gas, after leaving the tube is pumped through a purifying system, and then circulated back through the tube.

This type of light source, being capable of emitting fine lines, is well suited for use with the Littrow mount.
having large dispersion, for studies of hyperfine- and isotope-structures, and for the precise measurement of wavelengths.

This investigation was undertaken to develop, build, and study a light source of the hollow cathode discharge type, and the necessary auxiliary equipment such as the vacuum, circulating, purifying system, for use with the Littrow mount.

The construction of an insulating housing around the entire Littrow mount was one of several steps taken to suitably equip the spectrograph for this as well as for future investigations.

It is intended that this project be the first in a series of spectroscopic investigations using the equipment developed and studied here. With this in mind, detailed description is given of the methods of operating the vacuum system and the light source, and of lining up, and focusing the optical system with and without the etalon. Other suggestions are added with the hope that they will prove helpful to future experimenters.
Historical Background

The earliest form of hot hollow cathode discharge tube was developed by F. Paschen in 1916. His tube, shown in Figure 1, contains a box-shaped cathode made of sheet aluminum, open at both ends, and suspended by a wire through which electrical contact was made. The anode consisted of merely a wire, sealed through the glass wall of the tube. The tube was closed at the end with a quartz window, evacuated, and filled to a pressure of two millimeters with helium. The power was supplied from a 1000 volt battery, currents

![Figure 1. Paschen's Earliest Form of Hot Hollow Cathode Tube.](image)

...
ranging from 0.05 to 0.1 ampere. Paschen, studying the lines of helium, observed that the lines were very sharp due mainly to the small Stark effect.

Naude\textsuperscript{(3)} in 1929, slightly modified Paschen's tube, and Campbell\textsuperscript{(4)} in 1933, added still another change to the original tube. The resulting tube, shown in Figure 2, contains

![Figure 2. Campbell's Tube.](image)

a cylindrical cathode, C, eight centimeters long, with an internal diameter of fifteen millimeters, and walls of one millimeter thickness. This cathode, made of graphite was held by an iron wire spring, B, supported by wire which was sealed into the pyrex tube at S. The anode at A is made of
iron or nickel wire sealed in at P. A quartz window at W is located far enough from the cathode to prevent its becoming covered by material sputtered from the cathode. The bulb was used with a vacuum circulating system, the gas entering and leaving at Q and R.

This tube presented difficulty in interchanging samples on the cathode, and also in the cathode's heating excessively. This heating effect caused Doppler spreading of the lines, and also endangered cracking the pyrex bulb.

H. Schuler and H. Gollnow,\textsuperscript{(5)} in 1935, designed a hollow cathode tube which provided for water cooling the cathode, and for reducing the loss of material under investigation. The tube is shown in Figure 3. The cathode has six small

![Figure 3. Schuler and Gollnow's Tube](image-url)
radial holes located just below its opening. The exciting
gas is pumped in at the end of the tube near the window,
flows through the tube, forms an umbrella, or barrier layer,
over the opening of the cathode repelling the dispersing

Figure 4.
Tube Developed by Tolansky

particles of the material being investigated. The gas then
flows out through these small radial holes, through a ring
connecting these holes, passes through a groove in the out-
side of the cathode, and then back to the circulating system.
This tube has been used for investigations of pure metals and
compounds such as oxides, chlorides, and iodides.

More recently Tolansky\(^{(6)}\) has developed a tube which provides for easily interchanging cathodes. As shown in Figure 4, this tube has the anode and cathode insulated from each other by a closely fitted pyrex tube at P. Inside this tube is a water cooled mount into which the cathodes can be screwed. Water enters and leaves at R and S. This part and the outer part connecting with the anode are connected with a wax joint at T. By removing the wax sealed window at W easy access to the cathode is obtained. Tolansky found that the flow of gas through this tube also helped protect the window from becoming coated with the sputtered material from the cathode.

Schuler and Schmidt, in 1935 provided for more drastic cooling of both the cathode and anode by immersing a tube in liquid air as high as LL, shown in Figure 5. Thus the Doppler spreading was further reduced. This tube also provided a more convenient method of opening and resealing than had the previous tube of Schuler and Gollnow. However, the low temperatures caused the insulation between B and C to become porous. Thin paper saturated with apiezon grease was used as the insulation. By reducing the thickness of the paper, the seal served to hold a vacuum better, but increased the dangers of electrical breakdown.

Tolansky,\(^{(8)}\) in 1935 first developed a tube containing
a variable length cathode. In this tube the cathode is twenty-five centimeters long and is fitted with a movable plug. The plug can be adjusted according to the amount of current drawn, increasing the effective length of cathode for higher currents, and decreasing it for lower currents. This arrangement eliminates the effect of anomalous cathode fall when studying the effects of varying current. This tube is shown in Figure 6.

Paschen and Ritschl\(^{(9)}\) developed a discharge tube capable
of carrying currents up to three amperes without excessive broadening. The high currents made it possible to obtain the weak high series members of the spark spectrum of aluminum. The tube makes use of a long hollow cathode, open at both ends, and two cylindrical anodes, one located opposite each end of the cathode, as shown in Figure 7. Electrons can thus leave at both ends, reducing the electrical field. The tube is well suited for investigations of lines involving higher terms,
although not suited for lines having reversal effects.

Special purpose tubes have also been developed, such as those containing slit hollow cathodes for investigating high melting point metals which can be obtained in sheet form, and hollow cathodes for the study of Zeeman effect. Various hollow cathode tubes have been described here to serve as historical background.

The Littrow mount has been used by several workers at 688 Boylston Street. When new quarters were obtained at Commonwealth Avenue for the Physics Department the Littrow mount was disassembled and moved to its present location.
The Discharge Tubes Used

A. The First Design of Discharge Tube.

The tubes used as light sources in this research are modifications of the design originally used by H. Schuler and H. Gollnow. (1) Their original tube was more bulky and complicated than necessary. Hollow cathode tubes have been simplified, and modified for special applications, considerably since their first tube. The designs of the tubes used here (shown in Figures 8-A and 8-B) are such as to make for comparative ease in construction and assembly.

The first of these tubes (shown in Figure 8-A) is similar to that used by M. Gurevitch in 1949. (28) This tube contains a specially designed hollow cathode (shown in Figure 9). On the inner walls of the "hollow" is deposited a small amount of the material to be investigated. When the tube is in operation, light, emanating from the hollow cathode glow, passes up through the tube, through the opening in the circular anode, and out through the glass cover at the top end of the tube.

The material being investigated is conserved to a large extent by means of a barrier of inert gas formed at the opening to the hollow cathode. Inert gas, or air, at a pressure of from 0.1 to 2 millimeters of mercury, is circulated through the tube and the vacuum system by means of a mercury diffusion pump. The gas is forced into the tube at its upper
The First
Hollow Cathode Discharge Tube
Used as a Light Source

Figure 8-A.
HOLLOW CATHODE

RADIAL HOLES

ANODE

HOLE, AND SETSCREW, TO FASTEN LEAD.

GROOVES, FOR SPRING CLIPS

FIGURE 9-A.

FIGURE 10.
end, and passes downward inside the tube until it reaches the cathode.

The aluminum cathode has twelve small radial holes, 1/32 inch in diameter, located 1/8 inch below the opening of the hollow. The gas, upon reaching the hollow, travels outward through these small holes and passes down the outside of the cathode, to the bottom of the tube, and back to the circulating system. The gas, by streaming toward the cathode, and then out through the radial holes, forms a barrier, or "umbrella" over the opening to the cathode, driving back the vaporized particles of the element, and tending to prevent their dispersion and subsequent loss into the rest of the tube. In some tube designs almost all of the element can be reclaimed since most of that which does become dispersed is collected on the anode, and can be scraped off. The cathode is provided with hooks to make possible its easy removal without disturbing or dismounting the lower part of the tube.

The anode (shown in Figure 10) is so designed that it can be moved up and down to vary the spacing between cathode and anode. It is provided with spring clips, placed in grooves in the anode, and pressing against the inner wall of the glass part of the tube. This arrangement permits adjustment of the spacing between anode and cathode, and also allows for changes in the radial dimensions of the anode and the glass part of the tube as the temperature rises within the tube.
The hollow cathode tube can be separated into two parts, the upper made of glass tubing, and the lower made of copper tubing. The two parts are sealed together by a ring of beeswax and rosin. When the tube is being cooled at the cathode, heat is conducted away from the copper tubing walls, cooling the sealing wax, which becomes brittle and loses its sealing properties. If, on the other hand, the cathode is not sufficiently cooled when the tube is operating, so that the copper tubing becomes warm, the ring of wax will soften, and the vacuum will be lost. Hence a water jacket was built around the wall of the copper tubing, just below the seal. The temperature of the water circulating through this jacket is regulated so as to protect the seal from the effects of too high or too low temperatures. The outer copper tubing extending from the cathode to the location of the sealing cement has been made long to decrease the amount of cooling or heating at the seal.

Sufficient cooling for operating the tube was obtained by immersing the lower part of the tube in a bath of ice and water. More drastic cooling may be obtained by using a bath of dry ice and acetone.

The glass cover plate, or "window", located at the top end of the tube is sealed on with beeswax and rosin, (one to one ratio), which permits its easy removal.
B. The New Design of Discharge Tube.

The glass part of the tube just described suffered a fracture due to internal stresses in the vicinity of the ring seal. As long as the crack was small it was possible to maintain a vacuum by sealing it with cohesive rubber tape, and with beeswax and rosin. The crack eventually increased beyond repair and a vacuum could no longer be held. A new tube was then developed which did not require a ring seal.

This tube is shown in Figure 8-B. The inverted cup-shaped glass section previously used for supporting the glass part of the tube and for sealing the tube was omitted. The ring, or "crow's nest" of beeswax and rosin, as well as the cooling chamber beneath the ring were also omitted. Onto the upper end of the copper part of the tube was built a conically shaped section of copper about an inch and a half long. This was made to taper in at the upper end so as to come into contact with the glass part of the discharge tube. Three small glass beads, or knobs, were welded onto the glass part of the tube. These knobs were located such that they just rest on the upper edge of the conical copper section, when the tube is assembled. The upper glass part was thus supported on the lower copper part of the tube by means of these small glass beads.

The glass and copper parts were sealed together by wrapping with cohesive rubber tape. After the outer conical copper section had been fitted closely to the glass tubing,
NEW DESIGN OF HOLLOW CATHODE
GLOW DISCHARGE TUBE

Beeswax and Rosin seal
Lead to Anode
Area wrapped with cohesive rubber tape, covered with beeswax and rosin.
Gas Outlet
Level of Coolant
Small Radial Holes

Window
Gas Inlet
Glass Tubing
Glass Beads, welded to glass tubing, and resting on copper section.
Conical Copper Section

Anode, tapered
Hollow Cathode
Grooves to permit circulation
Thin Spacers

Figure 8-B.
a thin metal shim was carefully fitted over the connection between the glass and the metal. This prevented exposure of the rubber surface to the vacuum, and prevented intrusion of the rubber into the tube due to atmospheric pressure. This method is similar to that commonly used for sealing "but"-joints in metal-to-metal, metal-to-glass, and glass-to-glass connections. After the connection had been wrapped with the cohesive rubber tape it was covered with beeswax and rosin to further insure a vacuum tight joint.

An attempt was made to eliminate the glass beads and to rely on the tape alone for support. This was not successful, however, since a telescoping effect occurred as the system was evacuated, the glass part being forced by atmospheric pressure down into the metal part of the discharge tube. The amount of this drawing together, and hence the spacing between the anode and the cathode, was unpredictable.

Insulating mica spacers were made to fit between the anode and the cathode. It was intended that these mica spacers would insure against the tube's becoming short circuited, since the rubber tape alone could not be depended upon for support. However, when the discharge tube was in operation the metal which became vaporized from the hollow cathode plated onto the mica spacers forming a conducting layer which short circuited the electrodes. For this reason the insulating mica spacers were omitted, and the glass beads were welded in place to support the upper glass part of the tube.
In order to be certain that the anode, which previously had been mounted inside the glass tubing by spring clips, could not slip and come into contact with the cathode, a new method of supporting the anode was used. The bottom edge of the glass tubing near the anode was heated to the softening point, and crimped in under the anode at three or four equally spaced points around the circumference of the glass tube. This provided a support for the anode which was not adjustable, but which prevented any possibility of the anode's slipping. The spring clips were still used with the anode, for the purpose of centering the anode within the glass tube. A thin layer of mica, about a quarter of an inch wide, was wrapped around the anode and its spring clips, to provide insulation between the clips and the glass tubing. Previously the lower end of the glass tubing had cracked due to overheating while the tube was in operation. The points of contact between the spring clips and the glass tubing were the centers of stress, which hastened the cracking of the lower end of the previous tube. The mica was placed between the spring clips and the glass to minimize the localizing of stresses within the glass.

The upper end of the metal part of the tube was made conical in shape rather than cylindrical, so that the actual surface of contact between the glass and the metal would be very narrow in width. Before trying the conically shaped section, or collar, a cylindrical top section was built onto the metal part of the tube. This was carefully fitted to the
glass part of the tube.

However, due to the variations in diameter of both the glass tubing and the cylindrical collar, binding occurred at several places as the tube was assembled. It was feared that this binding between the comparatively large surfaces of contact would eventually cause considerable difficulty when assembling and disassembling the discharge tube. The glass part of one tube was broken in the process of assembling with the cylindrical type of collar. With the conical type of collar, however, the binding due to large and irregular surfaces of glass and metal in contact was eliminated, and this hazard was overcome.

There still remained the problems of adjusting the spacing between electrodes, and of centrally lining up the electrodes. Since the location of the anode was no longer adjustable in the vertical direction, the adjustment of the space between the electrodes had to be done by raising and lowering the cathode. When constructing the discharge tube extra space was left between the anode and the cathode. The cathode was then raised, reducing the space between electrodes, any desired amount by placing thin metal shims, or spacers, of various thicknesses under the cathode. The underside of the cathode was provided with grooves, and the spacers had holes drilled through their centers to allow circulation through the discharge tube.

In order to centrally line up the anode, the upper edge
of the conical copper sleeve was carefully filed as required at the locations of the glass beads. The support under one or the other of the glass beads was thus lowered slightly, and the angle of inclination of the glass part of the tube was adjusted as desired. This in turn adjusted the position of the anode, in a horizontal direction, since the anode is supported by the lower end of the glass part of the tube.

Once the anode had been lined up the relative position of the cathode was determined by viewing down into the tube. The cathode's position was next adjusted until it was located centrally with respect to the anode.

After the discharge tube has been sealed, and the system evacuated, the cathode may not be quite centrally located with respect to the anode. In this case it is still possible to adjust the position of the cathode without opening up the discharge tube. By gently tapping on one side or the other of the outside of the copper part of the tube, near the base of the cathode, the cathode can be made to "walk" or move about in any desired direction inside the discharge tube. The final centering of the cathode with respect to the anode was thus made without the necessity of opening and resealing the discharge tube.

Sufficient cooling of this tube to protect the seal was obtained by immersing the lower part of the tube in a bath of ice and water.
When future cold cathodes are made it is suggested that they be fitted tightly into the copper part of the tube to improve the dissipation of heat. It is suggested also that future hot cathodes have a section removed as shown in the figure at the right. This would leave a small diameter stem supporting the cathode on its base. The amount of heat conducted away from the hollow cathode by the metal would thereby be reduced. It seems advisable also to eliminate the small radial holes near the upper edge of the hot hollow cathode because there is ample space for circulation between the electrodes.

The metal parts of the tube, except for the changes previously described, were kept the same as for the first design of the tube. This makes it possible to have a versatile discharge tube since it can be used with either a cold hollow cathode when fine lines are desired, or a hot hollow cathode when intense lines are desired.
The Discharge

The discharge in a hollow cathode tube can be made to concentrate within the hollow of the cathode, under proper conditions of voltage and gas pressure. The voltage required to maintain the discharge is in the order of 300 to 500 volts. The cathode is a hollow metallic cylinder which may be open at one or both ends. The shape of the anode, however, is unimportant provided that it does not block off the light emitted from the tube. For a simple discharge tube such as that shown in Figure 11, a discharge of the Geissler type can be obtained when the pressure is reduced to the order of one centimeter. A glowing positive column exists outside the hollow, between the anode and the cathode. As the pressure is further reduced a point is reached where the

![Diagram of a simple discharge tube](image-url)
glow suddenly moves inside the hollow of the cathode and becomes very brilliant. The gas pressure for this is in the order of two to five millimeters and depends on the inside diameter of the hollow cathode.

By further reducing the gas pressure the discharge will glow more brilliantly at first, and then diminish until quite dim. At a critical value of pressure the discharge will cease to glow. This suddenly occurs at pressures in the order of 0.1 or 0.2 millimeter of mercury, or less. At this changeover pressure the resistance of the tube increases and the current decreases to a small value. There remains a feeble positive column glow located in the space between the cathode and the anode.

It has been shown by Gunther-Schulze that for a given current density on the cathode, the cathode potential fall for a hollow cathode is much less than for a plane cathode. This is due to the smaller loss of ions. The glow inside the hollow does not present a uniform appearance. As shown in Figure 12, there is a bright ring at (a) the cathode glow, a dark space at (b) the Crookes' dark space, and a bright central core at (c) the negative glow. The distribution of intensity in the negative glow of a hollow cathode is reversed from that of a plane cathode. The negative glow is most brilliant near the central axis of the hollow cathode. However, for a plane cathode the negative glow is brightest near the metal
electrode.

Both the arc and spark spectra of the gases in the hollow appear within the negative glow in general. The gradient of the electric field in the negative glow has been measured by Figure 12.

Hollow Cathode Glow

(11) Schuler who found it to be less than that of the positive column of a glow discharge. Hence there is almost no broadening of lines due to the Stark effect, under normal conditions.

The current density within the cathode remains constant, below a critical value of current. For small currents, a small area of the cathode wall is covered with glow. For larger currents proportionally larger areas are covered. The current density thus remains constant until the inside walls are completely covered with glow. If the current is increas-
ed beyond the point where the entire inside wall is covered with glow, the current density increases and an anomalous cathode fall sets in. This increases with further increase in current. Under these conditions of anomalous cathode fall Stark broadening does occur. Tolansky states that when the current density exceeds thirty milliamperes per square centimeter of inside wall in helium gas the potential fall becomes anomalous.

In the hollow cathode tube positive ions directed toward the cathode strike the cathode wall, or the material on the wall, and by a sputtering action eject metallic particles into the hollow. There is thus formed a vapor cloud of metallic particles which have been ejected into a region of intense discharge. These particles meet a concentrated flux of ions, and then are excited into spectral emission. It is generally agreed that the metallic particles are excited by collisions of the second kind. If the cathode is cooled the vapor pressure diminishes, but the sputtering action due to the positive ion bombardment still produces sufficient vaporization to obtain an intense spectrum.

There are differences of opinion as to the actual mechanism of excitation. One opinion is that the metal lining the inner wall of the cathode is removed by positive ion bombardment and evaporation. The bombardment produces very small intensely hot spots on the cathode, and from these the metal evaporates. The evaporated metal is emitted in an atomic
state and arrives at the negative glow by a process of diffusion. Some theories (13) maintain that the collisions occur between normal or metastable metallic atoms and metastable atoms or ions of rare gases. Others maintain that the metal on leaving the cathode is in an ionized state, and that the collisions are between metallic ions and excited metastable rare gas atoms. Sawyer (15) maintains that both types of collisions can exist in varying proportions, depending on gas pressure, cathode temperature, and current density. He maintains that for metals having low boiling points there are appreciable numbers of metal ions entering the reactions, while for metals having high boiling points or which sputter cathodically poorly the particles enter the discharge in helium in either the normal state or in a low metastable state of the atom.

When the gas pressure is reduced until the mean free path of the electrons leaving the inner wall of the cathode is nearly equal to the inside diameter of the hollow cathode a glow is produced. These electrons then have a mean free path which allows them to enter the region of the positive space charge of the opposite side of the hollow. The electrons reduce this charge and thereby lower the potential drop at the cathode. For stable conditions this results in an increase of current density. Whether the emission is predominantly arc- or spark depends on the exciting gas to a large extent. It is possible with helium, having a comparatively high excita-
tion potential, to excite most spark spectra. However, with argon, having a lower excitation potential, the arc spectrum is generally favored. Due to its small mass helium sometimes can not cause sufficient sputtering action. Argon, with its large mass, on the other hand, is more effective as a sputtering agent. A combination of argon and helium is sometimes used, the heavy argon increasing the sputtering action, and the higher excitation of helium producing a spark spectrum. If the arc spectrum is desired argon alone is sufficient. The concentrations of gas in the tube are quite low, hence the effects of pressure broadening are not encountered.
Doppler Effect

The cooling of the cathode decreases the line broadening due to the Doppler effect. The Doppler effect as observed in stellar spectra shows a shift of lines, indicating a change in the observed frequencies. The observed result is different, however, for spectra from a gaseous discharge in a tube.

In a gaseous discharge high velocities due to thermal agitation are attained. This is a random motion in accordance with the kinetic theory of gases. A resulting broadening, and not a shift, of lines is observed, due to the randomness of motion of the atoms and molecules emitting light. This broadening decreases with increasing atomic weight, and increases with temperature.

The change in the frequency of light emitted, $\Delta \nu$ for an atom moving at a velocity, $v$, and such that $\Theta$ is the angle between the direction of motion, and the observers line of sight can be obtained from

$$\frac{\Delta \nu}{\nu_o} = \frac{\nu - \nu_o}{\nu_o} = \frac{v \cos \Theta}{c} = \frac{\nu}{c}$$

where $\nu = \text{observed frequency}$

$\nu_o = \text{frequency when } v = 0$

$\nu = v \cos \Theta$, is the component of velocity in the direction of observation

$c = \text{velocity of light}$
According to Maxwell's law of distribution of velocities the probability that the velocity will lie between $u$ and $u+du$ is

$$d\omega = \sqrt{\frac{\beta}{2\pi}} e^{-\frac{\beta u^2}{2}} du$$

where $\beta = \frac{\mu}{kT}$, $\mu$ = molecular weight, $k$ = the universal gas constant, $T$ = absolute temperature

Solving for $u$ from equation 1:

$$u = \frac{c}{\nu_0} (\nu - \nu_0)$$

Substituting in equation 2:

$$d\omega = \sqrt{\frac{\beta}{2\pi}} e^{-\frac{\beta c^2}{\nu_0^2} (\nu - \nu_0)^2} du$$

Whence the relative intensity as a function of frequency, $I(\nu)$, is

$$I(\nu) = \text{(Constant)} e^{-\frac{\beta c^2}{\nu_0^2} (\nu - \nu_0)^2}$$

This relationship is plotted in Figure 13, giving an intensity frequency curve for the Doppler broadening of a spectral line.
The curve shown is for a general case where there is broadening due to the Doppler effect. The half intensity breadth may be found by setting the exponential part equal to one half, then solving for the half breadth ($v - v_o$) and multiplying by two.

$$\frac{1}{2} = e^{-\frac{\theta v^2}{v_o^2} (v - v_o)^2}$$

$$\log_e \frac{1}{2} = -\frac{\theta v^2}{v_o^2} (v - v_o)^2$$

$$(v - v_o)^2 = \frac{1}{\beta} \frac{v_o^2}{c^2} \log_e \frac{1}{2}$$

$$= \frac{1}{\beta} \frac{v_o^2}{c^2} \log_e 2$$

$$v - v_o = \frac{v_o}{c} \sqrt{\frac{1}{\beta} \log_e 2}$$

From: $\beta = \frac{\mu}{2RT}$, substitute:

$$\delta_d = v - v_o = \frac{v_o}{c} \sqrt{\frac{2RT}{\mu} \log_e 2}$$

From this equation it is seen that the Doppler effect is proportional to the square root of the absolute temperature. It is also proportional to the frequency and is inversely proportional to the square root of the molecular weight, $\mu$. 

The Littrow Mount

The components of the Littrow mount are supported on two parallel I-beams, thirty-one feet long. At one end of the I-beams is mounted a heavy iron frame containing the slit and plateholder. At the other end are mounted the collimating lens and grating. A small I-beam extension of three feet was bolted to the large I-beams at the slit and plateholder end of the Littrow mount. This extension was provided with a holder for supporting components of the optical system.

The slit and its Hartman diaphragm are located directly over the center of the plateholder. The slit is of the bilateral type, being opened by a calibrated screw, and closed by a spring. The slit can be pivoted about a vertical axis, moved in the direction of the light path, and clamped in position.

The plateholder is provided with means for focusing. A large adjustable screw moves the complete framework, containing plateholder and slit, in ways parallel to the light path. A large bolt at the center of the plateholder permits pivoting the plateholder about its center. Eight pairs of small adjustable screws, spaced along the upper and lower edges of the plateholder, provide for adjusting its curvature. Spring clips were made to hold the plates firmly in position. A removable light-tight cover was fitted onto the plateholder.
to protect the plates from stray light.

The collimating lens, near the far end of the I-beams is a six inch diameter acromatic lens of thirty feet focal length.

The grating is ruled on a plane glass surface coated with aluminum, and has 15,000 lines per inch. The ruled surface is 16.5 by 10.7 centimeters.

In order to minimize effects of building vibration the Littrow mount is suspended from above by sixteen heavy coil springs. The fastenings of these springs in turn are separated from the building by thick felt padding. Vibrations of the Littrow mount are further damped out by soft sponge rubber pads adjusted so that they lightly touch the Littrow mount. The inertia of the Littrow mount, due to its large mass, further reduces its susceptibility to vibration.

However, pumps which operate intermittently, and which are located in the sub-basement, cause sufficient building vibration to make the Littrow mount vibrate. This can be seen easily by placing a dish of mercury on top of the I-beams, shining a beam of light on the surface of the mercury, and observing the ripples on its surface when the pumps are in operation. This difficulty may be overcome by taking the exposures at night, when the pumps are not in use.

In order to obtain a more nearly constant temperature
for the Littrow mount and etalon, a housing made of wooden framework and one-half inch thick insulating Celotex panels, was constructed around the entire Littrow mount and etalon. Most of the material for this was salvaged from the previous location of the Littrow mount at 688 Boylston Street. This housing is three feet by three feet in cross section. It has hinged doors, seven removable sections which provide access to the equipment, and a raised section at the slit-plateholder end to provide full head-room for the operator. The operator can open and close sections of the housing to gain access to the slit, plateholder, grating, collimating lens, etalon, mirrors, lenses, baffles, and light stop, for making the necessary adjustments. This insulated housing also provides a light-tight enclosure for the interferometer, reduces stray air currents, and helps protect the enclosed equipment from dust.

Five baffles, made of Celotex, were placed at approximately equal intervals between the slit and collimating lens to cut out stray light. This is an important precaution with the Littrow type of mount. A small baffle, or stop, was placed at the focus of the light which is reflected from the back surface of the collimating lens. This small stop is suspended by wires in a manner which permits its adjustment in position. It can be moved along these wires until it coincides with, and blocks out, the small spot of reflected
light.

The entire inside of the housing, the baffles, and parts of the I-beams and mountings were carefully painted flat black to reduce stray light due to internal reflections.

Sensitive thermometers were placed in the housing to indicate the temperature.
The Optical System

A. The Optical System Without the Etalon.

The optical system without the etalon is shown in Figure 15. Light, passing vertically upward from the tube, is reflected through an angle of ninety degrees by mirror $M_2$. This mirror is placed directly above the end of the tube. The light passes through condensing lens $L_2$, is reflected by mirror $M_1$, and is focused on the slit. The collimating lens $L_1$ is placed at a distance equal to its focal length from the slit, hence the light, after passing through the slit and the collimating lens is parallel as it strikes the plane reflection grating $G$. The light is dispersed and reflected by the grating, and focused by the collimating lens on the curved plateholder $H$.

Light from a comparison source, such as an iron arc or a mercury arc, may be substituted into the system in place of the light from the hollow cathode discharge tube by adding a mirror to the system. The mercury arc is introduced by placing it off to one side of the tube, and placing a small mirror $M_3$ on top of the cover plate of the tube. Light from the mercury arc is reflected by mirror $M_3$ toward the rest of the optical system. Due to the physical dimensions the iron arc could not be used in the same location as the mercury arc. The iron arc is substituted by introducing a mirror $M_4$ between
Optical System Without Etalon

Figure 15.
lens $L_2$ and mirror $M_1$, and adding a lens $L_5$ near the iron arc, as shown in Figure 15.

The support for mirror $M_4$ is pivoted so that this mirror can be swung into and out of the light path. When this mirror is in the light path it not only reflects light from the iron arc toward the remaining components of the optical system, but also blocks out light from the tube, or from the mercury arc. When this mirror is out of the light path, the light from the tube, or mercury arc, traverses the system, and light from the iron arc does not.

B. Optical System With the Etalon.

The optical system with the etalon is similar to the optical system without the etalon, except that lens $L_2$ is replaced by two lenses, $L_3$ and $L_4$, and the etalon and diaphragm are added. This is shown in Figure 16. The light from the source is focused on the etalon by lens $L_3$, or by lens $L_5$ if the iron arc is used. The rings from the etalon are focused on the slit by lens $L_4$.

Slit widths in the order of half a millimeter were used.
Optical System With the Etalon

Figure 16.
Lining Up the Optical System

A. Without the Etalon.

For lining up the components of the optical system, a beam of light is first sent from a point near the center of the collimating lens, back to the source (hollow cathode tube, or other light source). This is accomplished by placing a small Mazda 90 bulb, rated 12 to 16 volts, close to the collimator lens, on the slit side of the collimator lens. The position of this bulb is adjusted until it is located centrally with respect to the collimator lens. A small wooden stand and wire holder were constructed for supporting this bulb. Adjustments of bulb position are easily made in any direction by bending the stiff supporting wire. The wooden base is cut to a size such that by lining up the end of the base with the edge of the I-beams, the bulb is correctly centered. This saves time when repeatedly using this bulb and stand.

Mirror $M_1$, as shown in Figure 15, is the first component of the optical system to be adjusted. The light from the small bulb passes back through the slit. Mirror $M_1$ is mounted in such a position that the light beam strikes it centrally. The mirror is then rotated about its vertical axis, until the reflected light falls beside the slit. The mirror is adjusted until its vertical axis is such that the elevation of the reflected light at the slit is the same as that of the slit itself.
Mirror $M_1$ is then rotated about its vertical axis until the reflected light coincides with an imaginary vertical line through the center of the source. The mirror is then turned about a horizontal axis until the light beam passes directly over the top of the tube, at a height of about two inches above the top of the tube. To facilitate this part of the lining up, two wood screws, about two inches long, to be used as markers, may be placed, head down, point up, on the glass cover plate of the tube. They should be located centrally over the side walls of the tube to indicate the position of the side walls. The observer can then watch for the light beam as it is adjusted to pass midway between these screws. The tips of the screws, furthermore, provide a measure for determining the correct elevation of the light beam as it passes over the tube. A check should be made to see that the light from the slit still strikes $M_1$ centrally.

The position of mirror $M_2$ is adjusted next. The light beam passing over the tube is now located such that it can strike mirror $M_2$ centrally. Mirror $M_2$ is mounted in position over the tube such that the surface of the mirror is at a forty-five degree angle with the horizontal. The small bulb and stand are now removed. Mirror $M_2$ is adjusted by running the tube, and moving $M_2$ until the light from the tube after being reflected from $M_2$ strikes $M_1$ centrally, and is reflected by $M_1$ to strike the slit centrally.
Lens $L_2$ is next mounted in position and adjusted until the light from the source strikes the slit centrally, fully covers the slit, and is focused on the slit.

The line-up can now be checked by observing the light coming from the source, from a position directly in front of the collimator lens, (on the slit side of the collimator lens). The observer can view the light coming through the slit, and by moving his head from side to side as well as up and down, can quickly determine whether or not the light will strike the collimator lens and grating centrally, and will fully illuminate the grating.

If this check should show that the light from the source does not illuminate the collimator lens fully and centrally, the adjustments described above should be repeated, using greater care and accuracy.

The grating is next adjusted to reflect the light through the opening in the plateholder. The grating is adjustable about three mutually perpendicular axes. By rotating about its vertical axis, referred to as the z-axis in Figure 17, (16) the order and spectral range can be selected. By rotating about the horizontal axis which lies in the plane of the

Figure 17.
grating, referred to as the Y-axis, the reflected image at the plateholder can be raised or lowered. By rotating about the horizontal axis which is perpendicular to the surface of the grating, referred to as the X-axis, the image at the plateholder is rotated in like manner about a horizontal axis perpendicular to the plateholder.

These three adjustments are made such that the desired spectral range is selected, and located symmetrically within the opening of the plateholder. As this condition is being approached the individual lines observed may not be uniformly illuminated. If this is the case, the line-up of the components of the optical system, in the vertical direction, should be rechecked, and then the grating rotated about the Y-axis until the lines are uniformly illuminated.

The mercury arc can be substituted easily for the hollow cathode tube as a light source without disturbing any of the components already in the system. To accomplish this a small mirror $M_3$ is placed on top of the tube, as shown in Figure 15, and the mercury arc is placed to one side of the tube. The distance from lens $L_2$ to the mercury arc is made equal to the distance from this lens to the glow discharge in the tube. Light from the mercury arc, after being reflected by mirror $M_3$ follows the same light path as that followed by light from the tube. The horizontal and vertical lining up of the mercury arc is accomplished by again placing the small bulb in
the same position as before near the collimator lens. The light from this bulb is viewed (from the location of the mercury arc) after it has traversed the optical system, and has been reflected toward the mercury arc by mirror $M_3$. The mercury arc is moved to intercept this light beam. The small bulb and its stand are then removed.

It is well to do the preliminary adjusting of the optical system using an iron arc as a light source because of the abundance of lines in the iron spectrum.
Lining Up the Optical System

B. With the Etalon.

When using the etalon the optical system is as shown in Figure 16. The lining up of the components is started in the same manner as for lining up the system without the etalon. The small bulb is placed just in front of the collimator lens, and located centrally with respect to it. The light from this bulb passes through the slit. Mirror $M_1$ is adjusted until the light coming through the slit strikes $M_1$ centrally. This mirror, and mirror $M_2$ are then adjusted as before. The small lamp and its stand are then removed.

The glow discharge is started within the tube, and lens $L_3$ is placed in the light path. It is adjusted so that the light from the source is focused at the position where the etalon is to be placed. This lens is then centered into the optical path. This is done by viewing the light coming through this lens from a position between the mirror $M_1$ and the slit. Lens $L_3$ is centered by moving it horizontally and vertically until the light coming through it is seen to strike mirror $M_1$ in the same central position that the light from the small bulb had previously struck mirror $M_1$.

The plates of the Fabry-Parot etalon must be accurately adjusted for parallelism before the etalon is placed in the optical system. (17) This is done by adjusting the ten-
tion on three spring clips which hold the glass plates in position. Three setscrews are provided for the purpose.

The etalon is illuminated with the mercury arc, and is turned so that the center of the rings is seen to coincide with the image of the pupil of the eye. Then, by moving the eye horizontally or vertically, while observing the rings, they can be seen to follow the motion of the pupil of the eye. If the rings expand when going in one direction, then the etalon plates are farther apart at that side than at the other. This is remedied by tightening the setscrews to reduce the spacing between the plates, and loosening the setscrews to increase the spacing. The same is done for motion in both the horizontal and vertical directions. When the plates are parallel there is no change in size of the rings, when moving the eye in any direction.

The etalon is placed in the system next, and its position is adjusted until light from the mercury arc is focused on it by lens \( L_3 \). The etalon is moved horizontally and vertically until it is fully illuminated, and is in the center of the light path. The etalon is then viewed from the side away from the source, with the observer's eye in the light path. The etalon is turned until the circular rings are seen to be located centrally. Since the rings are located centrally when they coincide with the reflected image of the observer's eye, it is helpful, when making this adjustment, to first
notice what part of the observer's face is reflected to his eye by the etalon plate. The observer then turns the etalon, as he would a small plane mirror, until he sees the image of his eye. When this is done the rings appear.

Lens $L_4$ is then placed in the system, and adjusted so that the light strikes the slit and the grating symmetrically. This lens is adjusted so that the fringes are focused on the slit.

For lining up and focusing the etalon, it is well to use the light from a mercury arc, so that the rings can be seen at the slit. These must be located centrally with respect to the slit, and illuminate the full length of the slit. Spectral lines may now be viewed at the plateholder.

After lining up and focusing the system with the mercury arc, it is replaced by the tube, merely be removing the small mirror $M_3$.

Since this light source is not monochromatic, the rings now will not be visible at the slit. In this case it is still possible to center the rings on the slit in the following manner. An electric light bulb of about sixty to one hundred watts is mounted near the collimating lens, in place of the small bulb. Light from this bulb, after passing through the slit is reflected by the etalon back toward the slit. The etalon is turned slightly, until this reflected image falls directly on the slit itself. The rings are now centered on
the slit, and the spectral lines broken up by the etalon, can be observed at the opening of the plateholder.

All adjustments must be made very carefully. Even though the light from $L_4$ strikes the slit centrally, the adjustments are so critical that the grating may not be illuminated centrally. In order to keep the grating fully illuminated while moving lens $L_4$ it was found helpful to put the small lamp and its stand again in place in front of the collimator lens. The small lamp is not turned on this time. The slit is opened wide. This results in a narrow black silhouette of the lamp and its holder, in the center of the spectral lines, as observed from the plateholder. If the lens $L_4$ is moved slightly to one side or the other during focusing, the spectral line likewise moves off to one side or the other of the black silhouette, and simultaneously decreases in intensity. Hence by keeping the spectral line centrally located with respect to the silhouette it is possible to focus by moving $L_4$ until the fringes can be observed at the plateholder. The small lamp and its holder are now removed. The system has been lined up.
Focusing

When focusing it is well to use an iron arc due to its abundance of lines. The focusing adjustments for the plateholder consists of: (1) a large setscrew which moves the complete framework containing the slit and the plateholder along tracks toward and away from the grating, (2) a bolt, mounted centrally with respect to the plateholder, about which the plateholder can be pivoted and fastened into position, and (3) eight pairs of setscrews for adjusting the curvature of the plateholder.

In the parallax method of focusing, fine wires are suspended vertically at intervals of three or four inches along the length of the opening in the plateholder. They are mounted such that they coincide with the location of the surface of the plate facing the grating. The wires and nearby spectral lines are observed simultaneously as the observer moves his head from side to side. If the plateholder is not in focus, relative motion between the wires and the spectral lines will be observed. When the plateholder is in focus this relative motion disappears.

The slant-plate method makes use of six plates, approximately five inches long by two inches wide, spaced at intervals across the plateholder. Slant-plateholders were made to hold these in position at an angle of approximately thirty degrees with the horizontal. The lower ends of the slant-
plateholders are closer to the grating, and the upper ends are farther away from the grating, than is the opening of the large plateholder. A fine wire, fastened across the center of each of the slant-plateholders, casts its shadow on the slant-plates to identify the position of each slant-plate with respect to the large plateholder.

The slant-plateholders, each containing a plate, are clamped in position, and an exposure taken using the iron arc. The lines on these plates are inspected to determine the locations of best focus for the various parts of the plateholder. The plateholder is then adjusted for these positions.

There is another method of focusing which determines the positions of best focus even more accurately. Six sets of exposures are taken. The plates used are two inches high by three inches wide, and are held in a vertical plane. The individual sets of exposures are taken at equal intervals of distance across the plateholder. Each set consists of several exposures taken at intervals of about one millimeter in front of, at, and behind the location of the opening in the plateholder. These plates are then inspected to determine the positions of best focus, and the plateholder is adjusted accordingly.
The Etalon

The Fabry-Perot interferometer contains two plane parallel glass plates, each partly silvered on one side. The silvered sides are placed toward each other and the glass plates are held in a rigid metal frame. A spacer of quartz or invar separates the plates. The spacer used here has three raised spots on each side, which are carefully polished, and against which the glass plates rest. Adjusting screws vary the tension of spring clips which hold the glass plates in place and which are located at the positions of the raised spots. The plates are adjusted for parallelism by varying the tension on these spring clips.

The interferometer makes use of fringes obtained in the transmitted light after the incoming light has been subjected to multiple reflections in air between the partly silvered surfaces. Fringes may be observed in the light transmitted through the etalon if the light is from a monochromatic source. Each ray of light, as it strikes the first silvered surface, is partly transmitted and partly reflected. That which is transmitted is again broken up into a transmitted and a reflected part by the second mirrored surface. The ray reflected from this surface strikes the first mirrored surface and again is partly transmitted and partly reflected. This process of multiple reflection continues, and from each
incoming ray there is obtained a number of parallel transmitted rays. These parallel rays are focused by a lens and interference fringes are produced.

![Figure 18](image)

**Figure 18.**

Figure 18 shows a ray striking the etalon at angle $\theta$. This ray is broken up by the multiple reflections and focused at a point $P_2$. Reinforcement of the rays is obtained when $2t \cos \theta = n \lambda$, where $n$ is an integer,

$$\lambda$$ is the wavelength,

and $\mu = 1$ for air between the plates.

This relationship may be obtained by considering **Figure 19.**

![Figure 19](image)
The difference in path between rays 1 and 2, \( BC + CD - BE \)

Due to symmetry

\[ BC = CD = \frac{t}{\cos \theta} \]

and

\[ BC + CD = \frac{2t}{\cos \theta} \]

likewise

\[ DF = BF = t \tan \]

and

\[ BD = 2DF = 2t \tan \]

so

\[ BE = BD \sin \theta = 2t \tan \theta \sin \theta \]

The difference in path

\[ = BC + CD - BE = \frac{2t}{\cos \theta} - 2t \tan \theta \sin \theta \]

\[ 2t \left( \frac{1}{\cos \theta} - \frac{\sin^2 \theta}{\cos \theta} \right) = \frac{2t}{\cos \theta} \left( 1 - \sin^2 \theta \right) \]

\[ 2t \cos \theta \]

For reinforcement the path difference is an integral \( n \) number of wavelengths, giving \( n \lambda = 2t \cos \theta \)

This condition exists for maximum reinforcement of the rays. As the angle \( \theta \) decreases \( \cos \theta \) increases, and \( n \) ceases to be an integer. The light is no longer bright, until \( \theta \) has decreased sufficiently for \( n \) to increase to the next integer. Maximum brightness is obtained for integral values of \( n \) such as 1, 2, 3, \( \ldots \).

The same relationships hold for any point \( P_2 \) located at the same distance from the axis. Hence a series of bright and dark concentric rings are obtained. These rings, or fringes are known as Haidinger fringes since they are observed near the normal, and the mirrored surfaces have a rather large separation.
A form of Fabry-Perot interferometer known as a "sliding interferometer" in which the spacing between the mirrors is adjustable, can be used when comparing light of two different wavelengths. If the plates are nearly together the rings from the two wavelengths almost coincide. If the plates are gradually separated, the rings separate and eventually fall half way between each other. As the plates are separated still further the rings coincide, and then separate again. Consider the rings at the center (cosθ=1) when the rings are midway between each other. Call the two wavelengths \( \lambda_a \) and \( \lambda_b \).

\[
2t_i = n_i \lambda_a \quad \text{for one wavelength}
\]

also

\[
2t_i = (n_i + \frac{1}{2}) \lambda_b \quad \text{for the other wavelength.}
\]

\[
2t_i = n_i \lambda_a = (n_i + \frac{1}{2}) \lambda_b
\]

substitute \( n_i \lambda_b \) from each term

\[
2t_i - n_i \lambda_b = n_i (\lambda_a - \lambda_b) = \frac{1}{2} \lambda_b
\]

since \( n_i = \frac{-2t_i}{\lambda_a} \)

substituting

\[
2t_i - \left( \frac{2t_i}{\lambda_a} \right) \lambda_b = \frac{\lambda_b}{2}
\]

\[
\frac{2t_i}{\lambda_a} (\lambda_a - \lambda_b) = \frac{\lambda_b}{2}
\]

\[
(\lambda_a - \lambda_b) = \frac{\lambda_a \lambda_b}{4t_i}
\]

If the difference between \( \lambda_a \) and \( \lambda_b \) is small,

\[
(\lambda_a - \lambda_b) = \frac{\lambda_a^2}{4t_i}
\]

If the spacing is increased until the sets of rings are again midway between each other (spacing is \( t_2 \)),

\[
2t_2 = n_2 \lambda_a = (n_2 + \frac{1}{2}) \lambda_b
\]
\[2t_i \cdot \lambda_a = (n_i + \frac{1}{2}) \lambda_b \]

\[2(t_2 - t_i) = (n_2 - n_i)\lambda_a = (n_2 - n_i)\lambda_b + \lambda_b\]

\[2(t_2 - t_i) = \left(\frac{2t_2}{\lambda_a} - \frac{2t_i}{\lambda_a}\right)\lambda_b + \lambda_b = 2(t_2 - t_i)\frac{\lambda_b}{\lambda_a} + \lambda_b\]

\[2(t_2 - t_i) \left(1 - \frac{\lambda_b}{\lambda_a}\right) = \lambda_b\]

\[\frac{\lambda_a - \lambda_b}{\lambda_a} = \frac{\lambda_b}{2(t_2 - t_i)}\]

\[\lambda_a - \lambda_b = \frac{\lambda_a \lambda_b}{2(t_2 - t_i)} = \frac{\lambda_a^2}{2(t_2 - t_i)}\]

Once the distances \(t_2\) and \(t_1\) have been measured, the difference between the known wavelength \(\lambda_a\) and the other wavelength \(\lambda_b\) can be determined.

This method, however, involves moving one mirror for each new setting. A more accurate method consists of photographing the fringes without changing the spacing between the plates. If the light source in this case consists of several different wavelengths the fringes will overlap and be confused with one another. However, if the etalon is crossed with an auxiliary dispersing device, such as the Littrow mount, the various wavelengths can be separated from each other, and the fringe systems can be observed. Relationships for the interferometer may be derived in the
following manner.

In general the order of interference will not be an integer \( P \), but will contain a fractional part \( \epsilon \), hence at the center (\( \theta = 0^\circ \), \( \cos \theta = 1 \)) the order of interference is \( p = P + \epsilon \). For a bright ring making an angle \( \theta \) with the normal, the order of interference is \( P = \frac{2t \cos \theta}{\lambda} \), hence in general at the center the order of interference is \( p = \frac{2t}{\lambda} \). By substitution, the order of interference for any bright ring is \( P = p \cos \theta \).

Let \( \phi \) = the angular diameter of a ring = 2\( \theta \).

substituting \( P = p \cos \frac{\phi}{2} \)

for small angles \( \cos \frac{\phi}{2} = 1 - \frac{\phi^2}{2!} + \frac{\phi^4}{4!} - \cdots \)

substituting \( P = p \left[ 1 - \frac{\phi^2}{2!} + \frac{\phi^4}{4!} - \cdots \right] \)

\[ P = \frac{p}{1 - \frac{\phi^2}{8}} = P \left( 1 + \frac{\phi^2}{8} \right) = P + P \frac{\phi^2}{8} \]

since \( \epsilon = p - P \)

substituting \( \epsilon = P + P \frac{\phi^2}{8} - P \)

\( \epsilon = P \frac{\phi^2}{8} \).

If now \( \theta \) = angle subtended at the condensing lens by standard gage marks on the slit.

\( L' \) = distance between these gage marks.

\( D' \) = the diameter of a ring on the slit.

\( L \) = corresponding gage marks photographed on the plate

\( D \) = corresponding diameter of ring photographed on the plate.
\( F = \text{focal length of lens} \)

\( m = \text{magnification of the spectrograph} \)

\[ \tan \phi = \frac{D'}{F}, \quad \text{and} \quad \tan \theta = \frac{L'}{F}, \quad \text{for small angles}. \]

and

\[ \phi = \theta \frac{D'm}{L'm} = \theta \frac{D}{L} \]

where \( D \) and \( L \) are the photographed dimensions on the plate.

Substituting

\[ E = P \frac{\phi^2}{\theta^2} = P \frac{\theta^2 D^2}{\theta L^2} \]

since

\[ m = \frac{L}{L'}; \quad L' = \frac{L}{m} \]

and

\[ \theta = \frac{L'}{F} = \frac{L}{mF}; \quad \theta L = \frac{1}{m} F \]

by substitution

\[ E = \frac{PD^2}{m^2 F^2} \]

since \( E = p - P \), and \( P = p (1 - \frac{\phi^2}{\theta^2}) \)

by substitution

\[ E = p - p + p \frac{\phi^2}{\theta^2} \]

so

\[ E = p \frac{\phi^2}{\theta^2}, \quad \text{and} \quad E = \frac{PD^2}{m^2 F^2} \]

(for a ring)

hence

\[ E = \frac{PD^2}{m^2 F^2} \]

call

\[ \frac{p}{m^2 F^2} = K \]

and for any bright ring

\[ E = KD^2 \]

For the first ring

\[ E + (n - 1) = E + (1 - 1) = E = KD_i^2 \]

For the second ring

\[ E + (n - 1) = E + (2 - 1) = E + 1 = KD_2^2 \]

subtracting

\[ 1 = K(D_2^2 - D_i^2) \]

or

\[ K = \frac{1}{D_2^2 - D_i^2} \]

Multiplying by the wavelength of any line \( \lambda \),

\[ K \lambda = \frac{\lambda}{D_2^2 - D_i^2} \]

This is a constant for any line on the plate,

since

\[ K = \frac{p}{m^2 F^2} \]
and \( K \lambda = \frac{\rho \lambda}{8 m^2 F^2} \)
making the substitution \( \rho \lambda = 2t \)

\[ K \lambda = \frac{2t}{8 m^2 F^2} \]
in which all terms are constants since \( m \) is considered a constant for the entire plate.\(^{(18)}\)

The method of obtaining wavelengths using the above relationships will be outlined. The diameters of the rings for each line are measured on a comparator. The diameters are squared, and the difference of the squares of successive rings, \( D^2 - D^2 \), is obtained. For greater accuracy two or three rings may be skipped over, and the difference between the squares of the diameters of say the second and fifth rings obtained, and divided by the number of spaces between rings.

\[ \frac{D^2 - D^2}{3}, \text{ or in general, } \frac{D^2 - D^2}{\alpha - \beta} \]

This is divided into \( \lambda \) giving the plate constant

\[ K \lambda = \frac{\lambda}{(D^2 - D^2)} \]
The plate constant is calculated for several lines, and the mean is used.

It is next desired to obtain the optical thickness of the etalon spacing, \( t \). However, it is first necessary to know the order of interference at the center,\((p)\).
The method of obtaining this order is next outlined. The plate constant is divided by the approximate known value of the wavelength \( \lambda \) for each line, giving \( K \) for each line.

\[ (K \lambda) \frac{1}{\lambda} = K, \quad \text{(obtained for each line)} \]
For each line these K's are then multiplied by the squares of the diameters
\[ K D_n^2 = \varepsilon + (n-1), \]
where \( n \) is the number of the ring, and \( \varepsilon \) is the fractional order. Two values of \( \varepsilon + (n-1) \) are thus obtained for each line and the average used for the fractional part of the order for each line.

The integral order of interference is next determined. The thickness of the spacer, \( t \), unless already known, is first obtained using a micrometer. This value is doubled, and divided by the standard wavelength of one line, giving \( \frac{2t}{\lambda_1} \), the work being carried out to the nearest integer. This value is now a trial at the integral order of interference. To this integral part is added the average value of \( \varepsilon \) (the fractional order) for that line, as described above. This order may not be correct in its integral part, but it has the correct fractional part. The integral part of the order, since obtained from \( \frac{2t}{\lambda_1} \) above, will not be correct unless the thickness, \( t \), is correct.

A trial value for \( 2t \) is now obtained by multiplying the complete order by the standard wavelength for this first line. This trial value for \( 2t \) is next divided by the known wavelengths of the other lines, giving trial values for the orders of interference for these lines. If the fractional orders obtained agree to within a few units in the second
decimal place then the true thickness of the etalon had been
determined, and the correct integral order for the first line.

However, if the fractional parts of the orders are not
in agreement with those previously calculated for these lines,
the thickness is not the true value. A new trial order for
the first line is then obtained by adding or subtracting a
unit from the integral part. Using this new trial order for
the first wavelength the procedure is repeated, multiplying
by the standard wavelength to obtain a new value for $2t$, $(P\lambda - 2t)$, and then dividing this value of $2t$ by the standard
wavelength of each line, giving new trial orders for these
lines. This procedure is repeated, each time adding or sub­
tracting one more unit from the integral part until the
fractional parts of the orders for all lines agree, as men­
tioned above, with the calculated fractional orders.

The true value of $t$ is now obtained from $2t = (P + \varepsilon)\lambda$
in which $P$ is the integral order obtained for each line,
$\varepsilon$ is the true fractional order previously calculated, and
$\lambda$ is the standard, or known, wavelength. The mean of these
values is used for the etalon thickness.

The final step in obtaining the refined value of wave­
length of each line is to divide the mean value of $2t$ by the
sum of the integral order obtained and the true fractional
order.
Determination of Wave-Lengths

The procedure just described was used in finding the wave-lengths of two cadmium lines. Mercury lines were used in determining the etalon thickness. A sample calculation is given in the Tables. Table I shows the method of determining ring diameters for the mercury line, \( \lambda = 4339.235 \, \text{Å} \). The spacings were measured with a Gaertner comparator, with the plate held at right angles to the carriage. Four sets of readings were taken with the end of the plate which contained the long wave-lengths placed toward the observer; and labeled "Red End Lower" in Table I. The plate was then turned end for end, and four more sets of readings taken. These are referred to under "Red End Upper" in Table II.

In Table II, column three, are listed the diameters obtained for "Red End Lower", and "Red End Upper". The mean is obtained in column four, and is squared in column five. Column six gives the difference in the squares of diameters divided by the number of rings skipped over. The last column gives the plate constant calculated for this line.

Table III, column one, lists the mercury lines photographed. Column two gives the values obtained for \( K \) for each line. These are multiplied by the squares of the diameters of the rings to obtain the fractional order of interference. The means of these fractional orders are given in column three. The value of \( 2\zeta \) given at the top of the last column was obtained from the previous work of Lacount\(^{18} \). An integral order
### Table I

<table>
<thead>
<tr>
<th>Ring</th>
<th>Standard $\lambda$</th>
<th>Red End Lower</th>
<th>One Side</th>
<th>Other Side</th>
<th>Diam.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4339.235</td>
<td>6.555</td>
<td>4.725</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.556</td>
<td>4.722</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.556</td>
<td>4.728</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.554</td>
<td>4.729</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.555</td>
<td>4.726</td>
<td>1.829</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6.135</td>
<td>5.118</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.130</td>
<td>5.116</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.130</td>
<td>5.115</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.128</td>
<td>5.114</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.130</td>
<td>5.116</td>
<td></td>
<td>1.014</td>
<td></td>
</tr>
</tbody>
</table>

### Table II

<table>
<thead>
<tr>
<th>Ring</th>
<th>Standard $\lambda$</th>
<th>$D$&lt;sub&gt;Red End Lower Mean&lt;/sub&gt; $D$&lt;sub&gt;Red End Upper&lt;/sub&gt;</th>
<th>$D^2$</th>
<th>$D^2_a - D^2_a$</th>
<th>$\lambda$</th>
<th>$D^2_a - D^2_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4339.235</td>
<td>1.829</td>
<td>1.834</td>
<td>1.8318</td>
<td>3.3540</td>
<td>1.8318</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.1602</td>
<td>3741</td>
<td>1.1602</td>
</tr>
<tr>
<td>2</td>
<td>1.014</td>
<td></td>
<td>1.019</td>
<td>1.0166</td>
<td>1.0335</td>
<td>1.0166</td>
</tr>
</tbody>
</table>
of interference obtained by dividing $2t'$ by the first wavelength listed in column one, is listed in the last column, the work being carried out to the nearest integer.

In Table IV, column two, orders of interference are given which were obtained by dividing $2t'$ by the wave-lengths of the first column. As a check on this value of $2t'$, in column three, one unit has been subtracted from the integral order for the first line, and the true value obtained for $E$ is added to this integral order. This order of interference was then multiplied by the wave-length of the first line, giving a new value for the double thickness of the etalon, $2t''$. This value was divided by the wave-lengths of each of the remaining lines, and the orders of interference listed in column three. This procedure is repeated again in column four, this time an integer being added to the integral order of interference of the first line. By adding and by subtracting an integer to the integral order of the first line

<table>
<thead>
<tr>
<th>Standard $\lambda$</th>
<th>$\frac{K\lambda}{\lambda}$</th>
<th>$\frac{K\lambda}{\lambda}D^2E_{(\text{Mean})}$</th>
<th>$\frac{2t'}{\lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5790.654</td>
<td>.6523</td>
<td>.760</td>
<td>32058</td>
</tr>
<tr>
<td>5769.59</td>
<td>.6547</td>
<td>.810</td>
<td></td>
</tr>
<tr>
<td>5460.740</td>
<td>.6917</td>
<td>.814</td>
<td></td>
</tr>
<tr>
<td>4358.35</td>
<td>.8667</td>
<td>.324</td>
<td></td>
</tr>
<tr>
<td>4347.496</td>
<td>.8688</td>
<td>.514</td>
<td></td>
</tr>
<tr>
<td>4339.235</td>
<td>.8705</td>
<td>.910</td>
<td></td>
</tr>
<tr>
<td>4077.811</td>
<td>.9263</td>
<td>.491</td>
<td></td>
</tr>
<tr>
<td>4046.561</td>
<td>.9334</td>
<td>.279</td>
<td></td>
</tr>
</tbody>
</table>

Table III

$(K\lambda=3777)$
### Table IV

<table>
<thead>
<tr>
<th>Standard $\lambda_n$</th>
<th>$\frac{2t'}{\lambda_n}$</th>
<th>$\frac{2t''}{\lambda_n}$</th>
<th>$\frac{2t'''}{\lambda_n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2t' = 18.564117$</td>
<td>$2t'' = 18.564102$</td>
<td>$2t''' = 18.564698$</td>
</tr>
<tr>
<td>5790.654</td>
<td>32058.762</td>
<td>32057.760</td>
<td>32059.760</td>
</tr>
<tr>
<td>5769.59</td>
<td>32175.800</td>
<td>32174.799</td>
<td>32176.805</td>
</tr>
<tr>
<td>4358.35</td>
<td>42594.367</td>
<td>42593.045</td>
<td>42595.701</td>
</tr>
<tr>
<td>4339.235</td>
<td>42782.004</td>
<td>42780.672</td>
<td>42783.342</td>
</tr>
<tr>
<td>4046.561</td>
<td>45876.281</td>
<td>45874.854</td>
<td>45877.716</td>
</tr>
</tbody>
</table>

### Table V

<table>
<thead>
<tr>
<th>Standard $\lambda$</th>
<th>$2t = p\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5790.654</td>
<td>18.564102</td>
</tr>
<tr>
<td>5769.59</td>
<td>18.564123</td>
</tr>
<tr>
<td>4358.35</td>
<td>18.564098</td>
</tr>
<tr>
<td>4339.235</td>
<td>18.564116</td>
</tr>
<tr>
<td>4046.561</td>
<td>18.564115</td>
</tr>
</tbody>
</table>

### Table VI

<table>
<thead>
<tr>
<th>Approx. $\lambda'$</th>
<th>E</th>
<th>$\frac{2t}{\lambda'} = p$</th>
<th>$\lambda = \frac{2t}{p}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4678.156</td>
<td>.442</td>
<td>39632.53</td>
<td>4678.1674</td>
</tr>
<tr>
<td>4799.918</td>
<td>.819</td>
<td>36675.89</td>
<td>4799.9275</td>
</tr>
</tbody>
</table>
in this manner, the fractional orders of the remaining lines were found to deviate from the true values of $E$, as previously calculated, hence the integral orders of interference are those obtained in the second column.

Table V gives values of $2t$ obtained by multiplying the integral orders of interference of Table IV, column two, plus the fractional orders of Table III, column three, by the wave-lengths of Table V, column one. The mean of these thickness is 18.564111. Table VI shows the true fractional order, $E$, in the second column for the cadmium lines of the first column. This was obtained by the same methods previously described, the cadmium red and green lines also being used in this work. In the third column the above value of $2t$ is divided by the wave-lengths of the first column, giving orders of interference. As a final step the integral parts of these orders plus the fractional parts as shown in column two are divided into $2t$ to give the wave-lengths shown in the last column.
The Vacuum System.

The vacuum system used with the hollow cathode tube serves also as a circulating and purifying system. Its functions consist of:

1. Drawing a vacuum on the tube.
2. Acting as a reservoir to supply an inert gas to the tube.
3. Providing for purification of this gas, and removal of any impurities already present in the system.
4. Pumping and circulating the inert gas through the tube.

The vacuum system used is shown in Figure 20. It consists of the following:

A. A mercury diffusion pump, to provide the low pressures required, and to produce a constant circulation of the gas through the system and through the tube. The diffusion pump is connected to a Cenco Hyvac mechanical fore pump at P.

B. McLeod gage.

C. Manometer.

D. and M. Cold traps to condense mercury vapor from the diffusion pump, McLeod gage, and manometer. These traps are immersed in baths of dry ice and acetone.

E. Reservoir of argon.
The Vacuum System

Figure 20.
F. Dehydrating agent.

G. Ground glass joint.

H. Glass tubing to copper tubing connection, sealed with Parra rubber tape over thin metal foil.

J. Hollow cathode discharge tube.

K. Glass tubing to glass tubing connection, sealed with Parra rubber tape over thin metal foil.

L. Calcium coated flask to act as a getter for purifying the gas.

P. Cenco Hyvac mechanical fore pump.

Pyrex glass was used throughout in the construction of the vacuum system. Stopcocks were added, as shown in the figure, for isolating various parts of the system, for connecting the system to, and isolating it from the Hyvac fore pump, for admitting small quantities of gas from the reservoir, and for admitting air from the atmosphere.

This circulating system and hollow cathode tube, in addition to being used for determining the spectra of solids, may be used also in determining the spectra of various gases. In such applications, the gas may be introduced into the system at tap 4.

Both helium and argon may be used as carriers in this system. The lighter helium gas has a high excitation potential, and a large energy transfer. Argon, being heavier, usually produces a more intense spectrum. Due to the fact
that argon freezes out at liquid air temperatures \(^{(20)}\) it
is well to use solid carbon dioxide for the cooling traps.
The Getter

The getter used in the vacuum system consists of a film of calcium evaporated onto the inner surface of a 500 millilitre round bottom flask. Many trials were made before a satisfactory method of evaporating the calcium was obtained. Early attempts resulted in failures, usually due to overheating, causing the heating coils to sag or to actually burn off, leaving an open circuit. In attempting to evaporate the calcium, various designs of heating coils were tried. These included horizontal helical coils, and conically shaped wire baskets of various materials and dimensions. Corrections of successive failures lead to the design used, as shown in Figure 21.

This design has several features. The complete element, including the wire basket, can be removed readily from the bulb, or flask, to facilitate cleaning and re-loading the wire basket. This has an advantage over designs which do not permit removal of the heating coil for re-loading. Although it is easy to re-load the basket, or heating coil, of such a model while it is inside the flask, it is quite difficult to clean off the ash-like residue, left from a previous charge of calcium, without damaging the wires. The residue generally has to be crushed and broken off of the wire basket, care being exercised to avoid damaging the basket in the process. Hence a removable element provides a simpler and safer way of
Arrangement for the Getter

Figure 21.
cleaning and reloading the wire basket.

The wire of which the basket is made is 0.025 inch diameter tungsten. Tungsten wire was eventually chosen because of its high melting point, 3700 degrees centigrade, and because it does not alloy with calcium upon heating. The 0.025 inch diameter wire was used because smaller diameter wires were found to lack the strength necessary to prevent excessive sagging under the weight of a charge of calcium, when heated sufficiently to evaporate the calcium. Wires of diameters greater than 0.025 inch had the necessary strength, but required excessive current to produce the required heating effect.

The basket is supported in a symmetrical manner which minimizes the sagging when heated. A small piece of mica insulation, shown in Figure 21, located opposite the upper "lead-in" wire to the basket, "catches" the basket as it starts to sag, supports it, and prevents the lower turns of the basket from being shorted out of the circuit.

The basket is silver soldered to two heavy copper supporting leads. The silver soldered joints and supporting leads are made sufficiently large to prevent failure due to overheating.

These leads, inside pyrex glass tubing, pass through the brass cover plate and the rubber stopper shown, and are silver soldered to short, 0.060 inch diameter, tungsten wires
which in turn are sealed to the glass tubing. This comparatively large diameter was chosen for the lead-in tungsten wires so that they will not overheat and damage the glass to wire seals when current is flowing. Vacuum tight seals are insured by water cooled, wax sealed (beeswax and rosin, one to one ratio) joints at the lead-in wires, and at the brass cover plate.

Tungsten wire is brittle, and cracks when bent under normal conditions. However, with the proper application of heat, it is possible to bend and wind tungsten wire into a coil. One way of doing this is to preheat, in a Bunsen flame, a metal form onto which the wire is wound. A woodscrew of the proper dimensions, heated and held firmly in a vice, serves nicely as a form for winding conically shaped wire baskets. Heat can also be applied intermittently to the wire itself using a soft flame, which makes winding without cracking still easier.

The heat and current required to evaporate the calcium without excessively heating the tungsten wire is estimated by first considering the temperatures required to sublime calcium at reduced pressures, and then obtaining these temperatures, approximately, by observing the color of the glowing wire basket when heated.

Consider, for example, conditions for evaporation when the system is evacuated to the comparatively high pressure of 61 microns. This corresponds to $8.1 \times 10^{-5}$ atmospheres.
According to the International Critical Tables, a temperature of approximately 925 degrees Kelvin, or 652 degrees Centigrade is required for subliming calcium at this pressure. From the Color Scale of Temperatures this temperature is found to correspond to a "dark red heat".

The basket does not heat uniformly, but is warmer near the central coils, and cooler at the top and bottom. The current is thus adjusted until the color is "bright red" near the central coils, diminishing to "dark red", and gradually to no glow approaching the top and bottom of the basket.

The evaporation is a rather slow process, requiring about ten to twenty minutes to form an opaque mirror-like film on the inner wall of the bulb. The current required is approximately ten to fifteen amperes. By using lower pressures, evaporation can be obtained at lower temperatures.
Operation of the Vacuum System

Before operating the vacuum system it should be checked to see that all stopcocks are properly greased, and turned to their correct positions. The glass tubing should be inspected for accumulations of stopcock grease which might obstruct the flow of gas through the system. These obstructions may occur in the glass tubing adjacent to the stopcocks, and should be cleaned out before operating the system. They can be reached by removing the cores of the stopcocks, and probing with a pipe cleaner. The hollow cathode discharge tube should be sealed into the system, after the material being investigated has been placed in the cathode.

The tube was designed so that it can be taken apart, and resealed easily. The outer copper tubing has a "crow's nest" or trough-like jacket built around it, into which a molten wax is poured. The inner glass tubing has an inverted cup-shaped section which fits down into the wax. When the wax solidifies the two parts of the hollow cathode tube are sealed together.

A mixture of beeswax and rosin was selected for this seal. These materials can be used to seal metal to glass without preheating either the metal or the glass. They form a good bond. They can be remelted and used over again a number of times. They are comparatively inexpensive, and readily available. They are well suited to the method of breaking the seal used here, since they soften at approximately 47 de-
grees Centigrade, and melt at a temperature ten degrees higher than this.

The undesirable property of the beeswax is that it shrinks when cooling and passing from a liquid to a solid.\(^{(24)}\) The amount of shrinkage was reduced by decreasing the ratio of beeswax to rosin. Samples of various proportions of beeswax and rosin were mixed, heated, and poured into small glass tubes to test for the amount of shrinkage upon solidifying. It was found that the smaller the ratio of beeswax to rosin, the less the shrinkage. Pure beeswax shrank considerably, leaving a "blow-hole" or hollow cavity in the mixture. Cavities likewise resulted for mixtures up to one part beeswax to ten parts rosin. By decreasing the ratio of beeswax to rosin still further the cavity disappeared, but the surface still hollowed in, when the material solidified. The ratio adopted for use, consisting of one part beeswax to twenty parts rosin, resulted in very little shrinkage, the surface being only slightly concaved on solidifying. Mixtures of this ratio also adhered well to the copper and glass, and could be resealed by the process described shortly.

Breaking this seal in order to take the tube apart is quite easy. All that is required is the circulation of hot water through the water jacket for about five minutes. The beeswax and rosin melts, and the two parts of the tube can be separated. Care should be taken to be certain that the
pressure inside and outside the vacuum system are equal before heating the seal. This is done by opening stopcock 4. If this is not done, some of the beeswax and rosin will be forced inside the hollow cathode tube as soon as the seal softens, and will have to be cleaned off later.

Various methods of connecting the tube into the vacuum system were tried before the method described below was finally adopted. The lower connection consists of a ground glass joint, part of which is connected to copper tubing by Parra rubber tape and a thin sheet of metal, and part of which is but-welded to glass tubing. The upper connection is made with Parra rubber tape and a thin sheet of metal. It is possible, by this arrangement, to remove and to replace either the entire tube, or the upper part alone.

One part of the ground glass joint is welded to the glass tubing of the vacuum system, and is therefore held rigidly in place. The other part of the ground glass joint is connected by Parra rubber tape and a thin piece of metal to the lower part of the tube. The copper tubing to which this joint is connected, being eighteen inches long, has considerable flexibility. This arrangement makes it possible to move the latter part of the ground glass connection a small amount. It can be pushed into, and pulled out of place, and can be twisted slightly. Hence the two parts of the ground glass connection can be "seated" or sealed together without putting strain on the glass parts of the system. In order to help with seat-
ing and unseating this ground glass joint the lower part of the tube can be rotated slightly, and moved about, bending the long copper tubing slightly as required.

Attempts at connecting the glass part of the tube into the system with a ground glass joint alone were not successful. Since the joint was to connect a rigid glass system to a large and rather heavy movable unit (the hollow cathode tube) it was quite difficult to make the ground glass joint seat properly and keep from leaking. It was difficult also to unseat this joint without breaking the glass tubing. The glass tubing did break in some attempts at unseating this kind of seal at this connection.

The connection made with Parra rubber tape, on the other hand, was found to work nicely in this application. It is dependable for holding a vacuum, does not place strains on the glass tubing, can be easily made, and can be opened without danger of shattering the glass tubing, by cutting the rubber tape with a razor blade.

A dehydrating agent such as silica gel is placed inside the tubing at the ground glass joint. A U-shaped was bent upward just beyond the part of the tubing which holds the dehydrating agent, to prevent it from falling into the rest of the system.

The calcium bulb is also sealed into the system before the system is evacuated. Finely divided calcium is placed in
the tungsten wire basket. The basket and supports are placed gently up inside the round bottom flask. The brass cover plates are sealed in place, and the ends of the leads are resealed with a one to one ratio of beeswax and rosin. The ends of the leads are connected to wire conductors and immersed in water cooling baths.

The system is evacuated as described below, and stopcocks 1 and 5 are turned so as to isolate the calcium bulb from the rest of the system.

The current in the basket is increased until the required temperatures are obtained for evaporating the calcium. After the calcium has been deposited on the inner wall of the flask the current is removed, and stopcocks 1 and 5 turned so as to connect the flask into the system.

The system is evacuated by operating both the mechanical fore pump, and the mercury diffusion pump. The mechanical fore pump (Cenco Hyvac pump) is started first, and the system is evacuated down to a pressure of a few hundredths of a millimeter of mercury. During this pumping the two-way stopcock, 1, is turned so that the Hyvac pump is connected to the system next to the mercury diffusion pump, and the system is closed at the other end. Stopcock 2 is turned to connect the tube into the system and isolate the reservoir from the system. Stopcocks 3 and 4 are closed. Stopcocks 5 and 6 are opened.

Since the system becomes evacuated sufficiently to permit
operation of the diffusion pump in a few minutes, it is well
to start the heater for the diffusion pump as soon as the fore
pump has been started, and to let the diffusion pump start
warming up while the fore pump is running.

Cold water is circulated continually through the cooling
chamber of the diffusion pump while the pump is in operation.
It is well to start the water circulating at the same time
that the heater for the diffusion pump is started. This pre­
caution will prevent accidental damage to the diffusion pump,
which could occur if the pump were allowed to heat up before
circulating the water in the cooling chamber.

Cold water is circulated also in the water jacket of the
hollow cathode discharge tube.

While the system is being evacuated the pressure can be
observed. The manometer is used until the pressure falls to
2000 microns. For lower pressures the McLeod gage is used.
Whenever the manometer is not being watched, stopcock 6 should
be in a closed position to prevent the mercury from rushing
back due to an accidental leak.

If the system is found to leak, stopcock 5, then stop­
cock 2, can be closed, one at a time, to isolate parts of
the system from the pumps and gage. The pumps are kept
running during this procedure. By watching the pressure,
that section of the system which contains the leak can be de­
termined.
If a leak should occur in the seal between the glass and the copper parts of the tube it can be resealed. A method of quickly resealing this connection consists of melting the top surface of the beeswax and rosin. A piece of steel of appropriate dimensions, such as a flat file, is heated in a flame to a red glow. It is then removed from the flame and drawn around the top surface of the seal, pressing down slightly into the beeswax and rosin. This should be done slowly enough to melt the seal to a depth of about one quarter inch. Since this resealing is carried on while the system is evacuated, the file should not be moved too slowly, nor be allowed to remain in any one location, since the beeswax and rosin can then soften all the way through to the bottom of the seal. A large leak would then develop due to the difference in pressure on the two sides of the seal. This remelting and resealing should be done carefully, seeing that the beeswax and rosin which is actually in contact with both the glass and the copper are melted. The steel blade, or file, should be kept hot enough to make the beeswax and rosin smoke during this process.(25)

After the system has been sealed it is evacuated to a pressure of one or two microns, or lower. Evacuation is continued at this low pressure for at least a half hour to clean impurities from the system. During this the two cold traps are immersed in baths of dry ice and acetone. The large ex-
posed sections of copper tubing are heated to drive off gas from the inside wall. Care should be taken not to heat the copper tubing to such an extent that the beeswax and rosin seal becomes soft. The cold water is kept circulating through the water jacket to help protect the seal.

During this cleaning out process stopcocks 6 and 2 are turned from time to time so as to clean out the short sections of tubing isolated by them.

The system is now ready to have argon added, and to be adjusted to operating pressure. With stopcock 3 closed, the seal of the argon flask is broken. In order to do this a small iron rod is placed inside the glass tubing which connects to the argon reservoir. The iron rod is raised by a magnet held outside the glass tubing. The magnet is removed and the iron rod drops onto the tip of the seal. The seal is broken and argon is released from the reservoir. Argon is let into the rest of the system by stopcocks 2 and 3. The argon flask is mounted with the seal on top, so that the broken glass can not get into stopcock 3.

Stopcock 1 is turned to isolate the system from the fore pump, and to connect both ends of the system together for the purpose of circulating gas through it. With stopcock 2 turned so as to isolate the reservoir from the rest of the system, stopcock 3 is opened for an instant and then closed again. This lets some argon into the tubing between stopcocks
2 and 3. With stopcock 2 closed, this argon is let into the system by turning stopcock 3.

Stopcock 3 is again set to isolate the reservoir, and to permit circulation through the system. The pressure is measured. If it is too low, more argon is added in the same manner. If the pressure is too high, the argon is allowed to circulate through the system a few minutes, and the system is then evacuated to the desired operating pressure. As the desired pressure is approached, it is measured at intervals of a few seconds.

When the correct pressure has been obtained the system is again isolated from the fore pump, and made into a circulating system by turning stopcock 1. The glow discharge is then started.
The Laboratory

The laboratory is located in room 51 of the Boston University Science Building. It consists of two rooms. The outer room is thirty-five by ten feet, and the inner room is thirty-five by five feet. The outer room contains the hollow cathode tube, vacuum system, and fore pump. The inner room is painted black, and contains the Littrow mount and etalon.

The laboratory is well-equipped with gas, air, water, 110 volts alternating current, and taps for various voltages of direct current. The direct current voltage desired can be selected by properly arranging the jumpers on the switchboard located in the motor-generator room of the sub-basement. Oxygen is obtained from the Air Reduction Sales Company, and dry ice from the Liquid Carbonic Corporation. An ice chest for the dry ice was made by lining the inside and cover of a heavy wooden box with a two inch layer of celotex.

The outer room has been made light-tight by sealing up the window with celotex. The celotex was painted black on the side facing the street so as to be inconspicuous. Felt padding, packed into the cracks between the window casing and the celotex, prevents light from entering the room through these narrow spaces. Various materials, including friction tape, Kex spackling compound, and strips of celotex, were tried in attempting to block out this light, but the felt
padding proved to be the most satisfactory.

The outer room, being light-tight and equipped with a sink and running water, can be used as a dark room for developing the photographic films and plates. This is more convenient than using the dark rooms on the second floor.

A sturdy work bench and vise, tables, drawers, and ample shelf space, help to make the laboratory practically self-sufficient. Power tools, including a lathe, drill press, and band saw, are available for use in the research building at 765 Commonwealth Avenue.

The automatic air conditioning unit in the room is unsatisfactory for use where close temperature control is important. When this unit operates, cold air, drawn in from outside the building blows along the wall at the end of the room. This air leaks in between the wall and the air conditioning unit, and sets up temperature gradients in the room as great as ten degrees centigrade over a distance of three or four feet. For this reason the unit was shut off, and the air intake from outside was completely blocked off with celotex and wood.

Steam pipes, located at the end of the black room, were covered by a layer of celotex to a height of nine feet above the floor.
The Power Supply

The electrical power supply consists of two full-wave rectifiers operated in parallel. These were purchased as war surplus material from the Atlantic Industrial Company, Ozone Park, New York, and are designated as "Power Supply PWR-1M". Each contains two type 1616 tubes. The choke input filter circuits each contain two ten-henry coils and two eight-microfarad, 1500 volt condensers. Across each filter output is a one megohm two watt resistor.

To the positive side of each power supply output are connected high wattage resistors of values suitable for limiting the current drawn to the desired values. Milliammeters are added in each circuit. The electrical circuit is shown in figure 22.

When the circuit is first closed the complete output voltage from the power supplies, approximately 1000 volts, appears across the gap in the hollow cathode tube. This serves to start the ionization within the tube. As the current builds up, the voltage drop across the series resistors increases. This reduces the voltage across the gap in the tube to the order of 400 to 500 volts.
The Electrical System

Figure 22.
Sample Interferometer Patterns.

**Figure 23.**

Mercury Lines:
- A: $5790.654\,\text{A}$
- B: $5769.59\,\text{A}$
- C: $5460.740\,\text{A}$
- $D_1$: $4358.35\,\text{A}$ (Overexposed)
- $D_2$: $4358.35\,\text{A}$

Cadmium Line:
- E: $4347.496\,\text{A}$
- F: $4339.235\,\text{A}$
- G: $4077.811\,\text{A}$
- H: $6438.4596\,\text{A}$
Results

A light source was desired which, in addition to other uses, eventually could be used for obtaining the spectra of rare materials. Such a source must be economical in its use of the materials under investigation. Hollow cathode discharge tubes fulfill the requirements, and it was suggested by Dr. Joos that a tube be developed similar to the one used by M. Gurevitch\(^{(28)}\).

This was the first of two tubes that were made. Both tubes provided for cooling the cathode and for repelling the dispersing particles of the material under investigation in the hollow cathode, by a barrier of gas pumped through the tube and through the circulating system.

A study of hollow cathode discharge tubes of previous workers revealed that one of the difficulties of these sources had been in devising satisfactory methods of sealing the tubes. A method of sealing with beeswax and rosin was developed for the first tube by reducing the ratio of beeswax to rosin in the sealing mixture, and by building up the seal in thin layers.

A second tube was developed which provided a simplified original method of sealing the tube, and at the same time provided a new method of mounting the upper glass part onto the lower metal part of the tube. The upper glass part was supported by three glass knobs which were welded onto the...
glass section. These knobs rested on a conical copper collar constructed on the lower part of the tube. Adjustment of the anode’s position was obtained by cutting away material from the supports under the glass knobs, thereby swinging the upper part of the tube, and the anode attached to it, into position.

Sealing was provided for by first fitting a thin metal shim over the glass-to-metal connection, and wrapping the connection with cohesive rubber tape. A mixture of beeswax and rosin was applied over the tape to further insure a vacuum tight connection. Other features were introduced in this new tube, among which was that of using the tube with either a cold hollow cathode for the production of fine lines, or with a hot hollow cathode for the production of more intense lines.

A vacuum, circulating, purifying system was also constructed for use with the light source. The system has the tripple function of providing the evacuation required to operate the tube, of providing for the circulation of gases through the tube, and of providing for purification of the gases in the tube and in the system. The purifier or getter makes use of calcium for the removal of impurities.

By correcting successive failures the present getter was finally developed. It contains a conically shaped wire basket of tungsten wire mounted in an erect symmetrical po-
position. Calcium, in a finely divided form, is placed in the wire basket which is heated electrically. When heated the calcium sublimes and deposits on the walls of the surrounding flask. One feature of this getter is that the element, consisting of the basket, supports, and sealing plate, can be removed easily from the flask to facilitate cleaning and reloading.

A celotex housing, with a wooden framework, was constructed around the complete Littrow mount. This provided for not only a more nearly constant temperature, but also a light-tight seal, the reduction of stray air currents, and the reduction of dust. Baffles for blocking out stray light, and supports for the components of the optical system, were constructed on the Littrow mount.

To eliminate large temperature gradients and air currents in the laboratory, the opening to the air intake was blocked off completely from outside the building, and the air conditioning unit was shut off. To further help with obtaining a more nearly constant temperature, the window in the laboratory, and the pipes in the dark room were blocked off by insulating walls of celotex.

Blocking out the window also provided a light-tight laboratory, suitable for photographic purposes.

The equipment developed in this project was tested with a readily available material. Cadmium was used, and wave-
lengths were determined using the Fabry-Perot interferometer crossed with the Littrow mount.

Detailed descriptions of the methods of using the equipment, such as operating the vacuum system, and lining up the optical system, are given to provide assistance to future workers.

Suggestions

A few suggestions are offered here with the hope that they may prove useful in the future: It is suggested that the McLeod gage be replaced by a continuously reading device, such as a Pirani gage.

Further work on the temperature control, perhaps using a thermostat, is suggested. (Long exposures were taken in the evening, the longest starting on a Saturday evening, and finishing early the next morning, in an attempt at working when the building was at the most nearly constant temperature).

It would be advantageous also to have the air intake provided with a cover, on the outside of the building, that can be opened and closed as desired. It would then be possible to open the cover, and operate the air conditioning unit, while working in the laboratory. The cover could be closed prior to, and during exposures, and the air conditioning unit shut off, to make temperature control possible.

Tighter fits on the cold hollow cathodes, possibly shrink
fits, and stem-and-base mounts for the hot hollow cathodes are suggested.

Acknowledgments

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Abstract

During recent years the interests of experimental spectroscopists have changed from the development of high resolution instruments to the development of light sources. One of the most promising types of light source is the hollow cathode glow discharge tube.

In view of this, the present research was undertaken to develop, build, and study a hollow cathode glow discharge tube and the necessary vacuum, circulating, purifying system, for use with the high resolution instrument already available, the Littrow mount. It is intended that this project be the first in a series of spectroscopic investigations using the equipment developed and studied here.

Numerous modifications have been made in hollow cathode light sources since their discovery by Paschen in 1916. Of prime importance among these is the work of H. Schuler who provided for cooling the cathode, thereby reducing the spreading due to the Doppler Effect. A light source of this type, being capable of emitting fine lines, is well suited for use with the Littrow mount having large dispersion.

The components of the Littrow mount are supported on two parallel I-beams thirty-one feet long. The collimator lens is a six inch diameter achromatic lens of thirty feet focal length. The grating is ruled on a plane glass surface coated with aluminum. It has 15,000 lines per inch on a
ruled surface 16.5 by 10.7 centimeters. The mount is supported from overhead by sixteen heavy coil springs, which in turn are separated from the building by thick felt padding in order to minimize the effects of building vibration. The inertia of the Littrow mount, due to its large mass, further reduces its susceptibility to vibration.

A housing of celotex was constructed around the entire Littrow mount in order to obtain a more nearly constant temperature, to provide a light-tight enclosure, and to reduce stray air currents. A set of baffles was provided to block out stray light.

A vacuum system was built for use with the light source. Evacuation is obtained by a mercury diffusion pump and a Cenco Hyvac fore pump. The system also contains a McLeod gage, a manometer, a reservoir of argon, a getter, two cold traps, and the discharge tube.

A getter was developed which consists of a film of calcium evaporated onto the inner surface of a round bottom flask. Calcium, in a finely divided state is placed in a small conically shaped basket of 0.025 inch diameter tungsten wire. The basket, supported by heavy lead-in wires, is sealed into the flask in a manner which permits its easy removal for cleaning and reloading.

By passing a current through the wire basket, the calcium is heated. It sublimes and slowly deposits as a film on the surrounding walls of the flask. Tungsten wire with its high
melting point, and an erect symmetrical mounting for the basket to minimize sagging when heated, were eventually selected.

The electrical power supply consists of two full-wave rectifiers (Power Supplies PWR-1M, 250 milliamperes, 1000 volts) operated in parallel. Each contains two type 1616 tubes, and choke input filter circuits. High wattage resistors are used to limit the voltage across the gap in the tube to the order of 400 to 500 volts.

The first light source developed for this project was a hollow cathode discharge tube in which there was an upper part made of glass, and a lower part made of copper. A circular anode, insulated electrically by the glass from the lower part of the tube, was supported by means of spring clips inside the glass tubing. These clips permitted adjustment of the position of the anode. The hollow cathode was fitted into the lower copper section.

The upper glass part and the lower copper part of the tube were sealed together with a ring of beeswax and rosin. In order to do this, a trough or "crow's nest" was constructed around the outside of the lower part of the tube. Into this fitted an inverted bell-shaped glass cup, which was welded to the upper glass part of the tube by a ring seal. The trough was filled with beeswax and rosin, sealing the two parts of the tube together. Beeswax shrinks upon solid-
ifying, leaving holes in the seal. However, it was found that by decreasing the ratio of beeswax to rosin in the mixture, the shrinkage was reduced sufficiently to eliminate the holes. Then by building up the seal in thin layers a vacuum-tight connection was obtained.

If the seal became too warm it softened, and if it became too cold it became brittle. In either case the vacuum was lost. A cooling bath, into which part of the lower section of the tube was immersed, was used to reduce the broadening of lines due to the Doppler Effect. This tended to lower the temperature of the seal, while the glow discharge tended to raise the temperature of the seal. In both cases the conduction of heat to and from the seal was through the copper part of the tube. Hence a protective water chamber was built around the copper part of the discharge tube just below the seal. The temperature of the water in this chamber was controlled to prevent the seal from failure due to excessive heating or cooling.

The glass part of the first tube suffered a fracture due to internal stresses in the vicinity of the ring seal. A new tube was then developed which did not require a ring seal. The inverted cup-shaped glass section, the sealing ring of beeswax and rosin, and the cooling chamber were omitted. After several trials, a new method of sealing the discharge tube, and at the same time of supporting the upper part on the lower part, was developed. Onto the upper end
of the copper part of the tube was built a conically shaped section of copper, which tapered in so as to come into contact with the glass part of the discharge tube. Three glass knobs were welded onto the side of the glass part of the tube in such a position that they just rested on the upper edge of the conical section, when the tube was assembled. The upper part of the tube was supported on the lower part by means of these small glass knobs. A thin metal shim was carefully fitted over the connection between the glass and the metal. The glass and copper parts of the discharge tube were sealed together by wrapping with cohesive rubber tape. The rubber tape was covered with beeswax and rosin to further insure a vacuum-tight seal.

In this tube the anode was centered by filing copper away from the supports under the glass beads, or knobs, thereby changing the position of the upper part of the tube and of the anode which is attached to it.

A new method of supporting the anode by crimping in part of the glass tubing, and of adjusting the electrodes was developed.

For both tubes the material being investigated is placed on the inside walls of the hollow cathode. Light, emanating from the hollow cathode glow, passes up through the tube, through the opening in the circular anode, and out through the glass cover at the top end of the tube.

Inert gas, or air, at a pressure of from 0.1 to 2.0
millimeters of mercury, is circulated through the tube and through the vacuum system by means of the mercury diffusion pump. The gas enters the tube at its upper end, passes downward inside the tube until it reaches the cathode, and forms a barrier, or "umbrella", over the opening of the cathode. The gas then flows outward through small radial holes just below the opening of the cathode, passes down the outside of the cathode to the bottom of the tube, and back to the circulating system. The barrier, or "umbrella", thus formed over the opening of the cathode drives back the vaporized particles of the material being investigated. This tends to prevent their dispersion and subsequent loss into the rest of the tube. Hence this type of source is useful for investigating small quantities of materials.

The new discharge tube is of simpler construction than is the first one. It is quite versatile also, since it can be used with either a cold hollow cathode, having a reduced Doppler Effect, when fine lines are desired, or a hot hollow cathode when intense lines are desired.

A Fabry-Perot interferometer was used to obtain interference fringes. The etalon was crossed with the Littrow mount which was used as the auxiliary dispersing device. Wavelengths of cadmium lines were determined with this equipment, using the hollow cathode discharge tube as a light source. The interference fringes were measured with a Gaertner comparator. The method of calculating wavelengths was outlined.
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Autobiography

The writer, Albert David Johnson, son of C. David and Ruth S. Johnson, was born in Worcester, Massachusetts, on July 15, 1918. He graduated from North Quincy High School in 1936. After graduating from Northeastern University in 1941 with a B. S. degree in electrical engineering, he worked for the General Electric Company. He received an A. M. degree in Physics at Boston University in 1946. From 1944 to 1946, and from 1948 to the present time, he has been teaching evening classes at Lincoln Institute. In 1948, after serving eighteen months in the army, he resumed his graduate studies at Boston University.