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**LIGHT SOURCES FOR THE EXCITATION
OF RESONANCE FLUORESCENCE IN CESIUM**

BY

DENNIS HUGH BURLING

**A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Physics in
Partial Fulfillment of the Requirements
for the Degree of Master of Science at
the University of Windsor**

**Windsor, Ontario
1966**

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ABSTRACT

The performance of the cesium radiofrequency lamps designed in this laboratory was compared with that of commercially available Osram lamps with respect to their ability to excite resonance fluorescence, and the half-widths and self-reversal of the emitted resonance lines. The shapes of the resonance lines were studied by means of a scanning Fabry-Perot interferometer which was built for this purpose. It was found that the radio-frequency sources emitted resonance lines of greater peak intensities, smaller degrees of self-reversal, and smaller half-widths than the corresponding lines produced by the Osram lamp. It was possible to resolve the h.f.s. splitting of the ground state and of the resonance state $^2P_{1/2}$ and to resolve partially the h.f.s. splitting of the $^2P_{3/2}$ state. The measured intervals between the various h.f.s. components were in satisfactory agreement with much more accurate values obtained elsewhere.

ACKNOWLEDGEMENTS

I should like to express my appreciation to Dr. L. Krause, under whose supervision this work was carried out, for his instruction and advice, and especially for his patient criticism of this thesis in manuscript form. I should also like to thank Dr. M. Czajkowski for introducing me to the intricacies of the proper utilization of the experimental equipment.

I wish to acknowledge the skilful craftsmanship of Master Glassblower W. Eberhart and Mr. W. Grewe, Superintendent of the Machine Shop, for their indispensable parts in the construction of various components of the interferometer.

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CHAPTER I

INTRODUCTION

Recent interest in studies of atomic resonance fluorescence and optical pumping has resulted in a demand for suitable spectral light sources. In order to excite resonance fluorescence efficiently, a lamp should emit resonance lines of high intensity, small half-width and no self-reversal. Most of the radiated energy will thus be available for the excitation of the atoms in the low density vapour.

The broadening of spectral lines may be due to several factors. At temperatures where the emitting atoms have significant thermal velocities, Doppler broadening increases the widths of the lines beyond their natural or radiation damping breadth. At almost all pressures of either the metallic vapour or of a foreign gas, collisions between the radiating atoms and other atoms cause collision broadening which is due to phase interruptions of the emission process. Collision broadening caused by the vapour pressure of the emitting atoms is always greater than that induced by collisions with inert gas atoms because in the first case the

interaction is of an exchange type, with an r^{-3} potential whereas in the second case van der Waals forces are involved with an r^{-6} potential. Stark effect can also be a source of line broadening, where large electric field gradients are produced in the discharge.

Self-reversal, which makes the centre of the line less intense than the wings, is caused by the reabsorption of the light as it passes from the centre of the lamp to the outside. Reabsorption is lessened by maintaining a low vapour pressure of the metal producing the required emission and by keeping the temperature constant throughout the volume of the discharge, to prevent the formation of a cooler layer of unexcited atoms at the walls of the lamp.

Many attempts have been made to meet the various and sometimes conflicting requirements. Commercially produced Osram lamps confine their a.c. discharge to a small cylinder of alkali resistant glass. The path from the emitting atoms to the outside is small, as is the volume of the discharge. The emitted resonance lines are strongly self-reversed.

Ernisch and Seiwert (1959) used a sodium lamp of Houtermanns' design which incorporated the use of alkali resistant glass to reduce the discolouration resulting

from the corrosive action of the alkali vapour. It was found that the soft glass cracked because of annealing problems and of large temperature gradients across the glass surface.

Large currents in a.c. discharge lamps, used to prevent condensation of high melting-point metals, result in the broadening of spectral lines. Cario and Lochte-Holtgreven (1927) found that a discharge lamp could be run at a low current by circulating an inert gas in a direction from the exit window toward the stream of hot vapour coming from the heated metal, to prevent condensation on the window. Using a lamp of this type, Hoffman and Seiwert (1960) obtained a smaller self-reversal than with the Osram lamp which, however, was accompanied by a smaller emission intensity.

The cataphoresis lamp designed by Bruyvesteyn (1935) was also studied by Hoffman and Seiwert (1960). The discharge was maintained by a carrier gas while the metal was evaporated near the hot cathode. Relatively few metallic ions reached the exit window near the anodes and no deposition of metal was observed. Hoffman and Seiwert found the self-reversal in the potassium cataphoresis lamp much smaller than with the Osram lamp.

Bell, Bloom and Lynch (1961) experimented with electrodeless radio-frequency lamps operating at 30 Mc. Self-absorption was reduced to a minimum by means of the skin effect, but the intensity of the lamp slowly oscillated with a time-constant dependent upon thermal capacity. This instability was reduced by the use of heavier inert carrier gases. Gerard (1962) produced a design for an rf. lamp that could be constructed in the laboratory, with the vapour pressure of the alkali metal controlled by an external heating coil. Gerard's design was modified and applied to the construction of potassium and rubidium spectral lamps by Atkinson, Chapman and Krause (1965) who carried out a systematic study of these light sources and compared them with commercially available units.

In the present investigation a pressure-scanning Fabry-Perot interferometer was built and was used to study cesium lamps. A light source, constructed according to the design of Atkinson, Chapman and Krause, was compared with an Osram lamp as to efficiency of exciting cesium resonance fluorescence, spectral line width and self-reversal. The pressure scanning photoelectric interferometer, which supersedes the fixed instrument with photographic recording,

used in the previous studies, has been proven to be a versatile tool for studies of spectral line profiles.

CHAPTER II

THE THEORY OF THE FABRY-PEROT INTERFEROMETER

When light of wavelength λ falls upon a pair of Fabry-Perot plates separated by an air gap t cm. thick, a series of concentric fringes is formed. Since all the light incident along the surface of a cone of semi-angle θ , formed by the incident light and the normal to the plates, contributes to form a single circular fringe, the condition for constructive interference is

$$\lambda n = 2\mu t \cos\theta \quad (1)$$

where n is the order of interference and μ is the refractive index of the medium between the plates.

$\cos\theta$ is a maximum when $\theta = 0$ and the highest order of interference occurs at the central fringe. n decreases by one with each ring, while moving radially outwards from the centre of the fringe system.

By differentiating Eq. (1) it is found that at the centre of the system,

$$d\gamma = \frac{dn}{2\mu t} \quad (2)$$

where γ is the frequency in cm^{-1} . Thus the spectral range between two successive orders ($\Delta n = 1$) is

$$\Delta\gamma = \frac{1}{2\mu t} \quad (3)$$

At the centre of the fringe system where $\cos \theta = 1$,

$$n = 2\mu t \nu. \quad (4)$$

Differentiation of Eq. (4), with ν and t constant, gives

$$dn = 2t \nu d\mu. \quad (5)$$

In using the Fabry-Perot etalon as a spectrometer, a spectral range is scanned by changing the index of refraction of the air between the plates which, in turn, is a function of pressure.

If $t = 1$ cm. is used in a study of the sodium D lines, a change of approximately 10 orders takes place at the central fringe for a pressure change from vacuum to one atmosphere, since the corresponding change in the refractive index is 0.0003. Thus, if the light at the central fringe is observed with a photomultiplier tube, the shape of the spectral line can be obtained as several successive orders pass the centre of the interference pattern.

According to Rayleigh's criterion, the resolving limit of a spectrometer is defined as follows:

$$d\nu = \nu \frac{d\lambda}{\lambda}, \quad (6)$$

where $\frac{\lambda}{d\lambda}$ is the resolving power. The resolving limit is a direct measure of the instrument's ability to separate two closely lying spectral lines. The resolving power changes over the spectrum but the resolving limit remains constant.

The resolving limit $d \nu$ at the centre of the fringe system may be found as follows: (Tolansky, 1947)

$$n = n_0 \cos \theta, (\cos \theta = 1) . \quad (7)$$

Therefore
$$n = n_0 \cos \left(\frac{\phi}{2} \right) \quad (8)$$

where ϕ is the angular diameter of an interference fringe of order p and $n = n_0 - p$. (9)

Thus

$$n = n_0 \cos \left(\frac{\phi}{2} \right) = n_0 \left\{ 1 - 2 \sin^2 \left(\frac{\phi}{4} \right) \right\}^{\frac{1}{2}} \approx n_0 - n_0 \frac{\phi^2}{8} . \quad (10)$$

The angular diameter (in radians) of the p^{th} ring is

$$\phi = \left(\frac{8p}{n_0} \right)^{\frac{1}{2}} . \quad (11)$$

Since the order of interference at the centre of the fringe system is usually not an integral value, let ϵ_1 (where $\epsilon_1 < 1$) be the fractional order. Therefore the order of interference at the first fringe is $n_1 + \epsilon_1$.

Since n_1 is the order of the first ring, the order of the p^{th} ring is $\phi_p = \left(\frac{8}{n_0} \right)^{\frac{1}{2}} \left((p-1) + \epsilon_1 \right)^{\frac{1}{2}} . \quad (12)$

If the interference fringes, localized at infinity, are focussed with a lens of focal length f , the resulting linear diameter of the p^{th} ring is

$$D_p = f \phi_p = \frac{f \cdot 8^{\frac{1}{2}}}{n_0^{\frac{1}{2}}} \left((p-1) + \epsilon_1 \right)^{\frac{1}{2}} , \quad (13)$$

and

$$D_p^2 = \left(\frac{8f^2}{n_0} \right) \left((p-1) + \epsilon_1 \right) . \quad (14)$$

ϵ_1 is found by measuring the fractional diameters of any two adjacent rings.

$$\frac{D_p^2}{D_{p+1}^2} = \left(\frac{\epsilon_1 + p - 1}{\epsilon_1 + p} \right) \quad (15)$$

and
$$\epsilon_1 = \frac{D_{p+1}^2}{D_p^2 - D_{p+1}^2} - p \quad (16)$$

For two closely lying spectral lines with respective fractional orders ϵ_1 and ϵ_2 at the centre of the interference pattern, the frequency difference between the two lines is given by $\left(\frac{\epsilon_1 - \epsilon_2}{2t} \right)$.

For adjacent rings of orders p and $p + 1$ arising from the first line,

$$D_{p+1}^2 = \frac{8f^2}{n_1} (p + \epsilon_1) \quad (17)$$

$$D_p^2 = \frac{8f^2}{n_1} (p - 1 + \epsilon_1) \quad (18)$$

and
$$D_{p+1}^2 - D_p^2 = \frac{8f^2}{n_1} = \Delta_1 \quad (19)$$

Since n_1 is the order of interference of the first fringe, the difference of the squares of the two adjacent ring diameters is a constant.

Similarly, for the second line

$$d_{p+1}^2 - d_p^2 = \frac{8f^2}{n_2} = \Delta_2 \quad (20)$$

where n_2 denotes the order of interference of the first fringe arising from the second line.

Taking $n_1 = n_2$, and $\Delta_1 = \Delta_2 = \Delta$, (21)

$$\epsilon_1 = \frac{D_{p+1}^2}{D_{p+1}^2 - D_p^2} - p = \frac{D_{p+1}^2}{\Delta} - p \quad (22)$$

and

$$\epsilon_2 = \frac{d_{p+1}^2}{d_{p+1}^2 - d_p^2} - p = \frac{d_{p+1}^2}{\Delta} - p \quad (23)$$

$$\epsilon_1 - \epsilon_2 = \frac{(D_{p+1}^2 - d_{p+1}^2)}{\Delta} \quad (24)$$

But

$$dV = \frac{(\epsilon_1 - \epsilon_2)}{2t} \quad (25)$$

therefore $(D_{p+1}^2 - d_{p+1}^2)$ is a constant.

$$\text{Since } D_{p+1}^2 - D_p^2 = \frac{8f^2}{n_1} = \Delta = \frac{8f^2}{n_2} \quad (26)$$

$$dV = \frac{1}{2t} \frac{D_{p+1}^2 - d_{p+1}^2}{d_{p+1}^2 - d_p^2} \quad (27)$$

Therefore, to calculate the resolving limit, it is only necessary to find the differences of the squares of successive ring diameters corresponding to a given spacer thickness.

CHAPTER III

THE SHAPES OF THE SPECTRAL LINES OF CESIUM

A) Resonance Lines of Alkali Metal Atoms

Resonance radiation is emitted when an atom is excited to a higher state from the ground state and, in returning to the ground state emits a photon, with no possibility of transitions to intermediate states.

In alkali metal atoms the ground state is the $n^2 S_{\frac{1}{2}}$ and the resonance states are the $n^2 P_{\frac{1}{2}}$ and $n^2 P_{\frac{3}{2}}$, where $n = 3$ for sodium, 4 for potassium, 5 for rubidium and 6 for cesium. A doublet structure exists because of the fine structure splitting in the P levels.

$$J = S + L = \frac{1}{2} + 1 = 3/2$$

and $J = S + L = -\frac{1}{2} + 1 = \frac{1}{2}$, where J , L , and S are the total, orbital, and spin quantum numbers respectively. The selection rules are $\Delta L = \pm 1$ and $\Delta J = \pm 1, 0$.

Hyperfine structure results from the fact that the nucleus may have a resultant spin and a corresponding magnetic moment. If I is taken as the nuclear spin quantum number, then the total angular momentum is $J + I = F$ where F is the hyperfine quantum number that can have any value in the range

$$|J + I| \geq F \geq |J - I|. \text{ If } J \geq I, \text{ there exist}$$

$2I + 1$ values of F ; for $I \geq J$ there are $2J + 1$ values.

The selection rule $\Delta F = \pm 1, 0$ holds for transitions from one hyperfine structure level to another, but $F = 0 \longrightarrow F = 0$ is forbidden.

The energy differences between levels of a hyperfine structure multiplet are given by the ratio $(J + 1)$:
 $(J + I - 1), \dots, -J - I$. The ratio of the sums of the intensities of all transitions from two adjacent h.f.s. states F_1 and F_2 are in the ratio of their statistical weights $(2F_1 + 1) / (2F_2 + 1)$. When the h.f.s. splitting of one of the levels, between which an optical transition is allowed, is negligibly small, the intensities of the transitions are in the ratio of the values $(2F + 1)$ for the h.f.s. of the level whose splitting produces the structure. This situation exists in the resonance lines of alkali or alkali-like spectra in which the h.f.s. splittings in the ground states are about ten times larger than in the resonance states.

Hyperfine splitting also results when an element has several isotopes, each contributing its own line. The lines are separated by a small amount dependent upon the charge and mass distributions in the atoms of the respective isotopes.

B) Theoretical Calculations of Line Shapes

The intensity distribution of a spectral line may be calculated theoretically. The basic shape, the resonance distribution or natural line width, results from the electron configurations of excited levels in the emitting atoms. Broadening effects caused by collisions with like or foreign atoms add to the width of the line, while self-absorption of the emitted light by like atoms deforms the shape by producing a characteristic dip in the centre of the line.

(i) Radiation Damping

According to the classical description, excitation of an atom occurs when the atom receives an impulse that displaces one or more electrons from their equilibrium positions and sets them into oscillation. An oscillating electron radiates according to the laws of dipole radiation, and is subject to an elastic restoring force, and to a radiation reaction force acting when the acceleration is changing. Since the radiation represents a loss of energy, the electron executes a damped vibration and the total radiated power decreases exponentially. The exponential time constant is of the order of 10^{-8} seconds and is called the average lifetime of the excited state of the atom. The spectral shape is found by a

Fourier analysis of the distribution of radiated flux density over the spectral range. The resonance distribution function is

$$I(\nu) = \frac{\gamma}{2\pi} \frac{1}{(\nu_0 - \nu)^2 + \left(\frac{\gamma}{2}\right)^2}. \quad (28)$$

The half-width γ , expressed in units of wave length, is independent of the wave length of the line.

In the quantum representation, the natural line width is a result of the fact that each of the two energy levels E_1 and E_2 , between which a transition has the possibility of occurring, is not infinitely sharp; each has a finite width, ΔE_1 and ΔE_2 . On the basis of the quantum theory, Weisskopf and Wigner (1930) obtained the following expression for the natural line profile.

$$I(\nu) = \frac{(\gamma/2\pi)}{[(\nu_{21} - \nu)^2 + (\gamma/2)^2]}, \quad (29)$$

which is equivalent to Eq. (28). In Eq. (29), ν_{21} is the Bohr frequency $\frac{(E_2 - E_1)}{h}$ and γ , the half-width, is given by

$$\gamma = \gamma_1 + \gamma_2 = \frac{\Delta E_1}{h} + \frac{\Delta E_2}{h}. \quad (30)$$

On the basis of the quantum theory of radiation it is possible to obtain the following expression for the natural half-width.

$$\gamma = \frac{4\pi e^2}{mc^3} (\nu_{21} f_{21}), \quad (31)$$

where m is the electronic mass and e the charge, and f_{21} is the oscillator strength of the transition from E_2 to the ground state E_1 . Quantum theory predicts that f_{21} should depend on the oscillator strength of the transition and should not be the same for all spectral lines.

(ii) Doppler Broadening

Significant broadening of a spectral line may be caused by the thermal motions of the gas atoms. If all emitting atoms were at rest a sharp frequency ν_0 would be observed. However, when the emitting atoms have a velocity component v_x in the line of sight of the observer, the Doppler effect predicts that the observer will see a frequency

$$\nu = \nu_0 \left(1 - \frac{v_x}{c} \right) \quad (32)$$

The fractional number of these atoms within a range dv_x is

$$\frac{dn}{n} = \left(\frac{M}{2\pi RT} \right)^{\frac{1}{2}} \exp. \left[-\frac{(M)}{2RT} v_x^2 \right] dv_x, \quad (33)$$

where M is the molecular weight of the gas. This also represents the fraction of the total intensity that is emitted at a frequency ν .

Expressing v_x in terms of ν ,

$$I(\nu) = \left(\frac{Mc^2}{2\pi R T \nu_0^2} \right)^{\frac{1}{2}} \exp. \left[\left(\frac{-Mc^2}{2 R T \nu_0^2} \right) (\nu - \nu_0)^2 \right]. \quad (34)$$

Thus the Doppler effect produces a Gaussian distribution for the absorption or emission line.

$$\text{The half-width is } \Delta \nu_{\frac{1}{2}} = 2 (\log 2)^{\frac{1}{2}} \left(\frac{2 R T}{Mc^2} \right)^{\frac{1}{2}} \nu_0 \quad (35)$$

$$\text{or, in the wavelength scale, } \Delta \lambda_{\frac{1}{2}} = 2 (\log 2)^{\frac{1}{2}} \left(\frac{2 R T}{Mc^2} \right)^{\frac{1}{2}} \lambda_0. \quad (36)$$

While the natural line width on a wave length scale is approximately invariant with wavelength, Doppler broadening decreases with wave length.

(iii) Stark Broadening

The emitting atoms or ions in a plasma are under the influence of electric fields produced by rapidly moving electrons and slowly moving ions. According to the impact theory, the emitting systems may be unperturbed most of the time. The electron impacts which create rapidly varying fields are well separated in time. The quasistatic or statistical theory, derived by Holtsmark, treats the slow moving ions. The perturbation is considered nearly constant in time and a static approximation is used to find the ion-

field distribution. Holtzmark divides the broadeners into ions, dipoles and quadrupoles. A certain spatial configuration of the broadeners results in a field at the emitter, the magnitude of which depends upon the type and geometry of the broadeners. The intensity distribution of a Stark-broadened line, of frequency ν , is given by

$$I d\nu = d\nu \int_0^{\infty} I(E, \nu) W(E) dE, \quad (37)$$

where $W(E)$ is the field strength probability which depends on the type and spatial distribution of the broadeners, and E is the electric field strength. (Holtzmark, 1919).

For broadening due to ions the half-width is

$$\Delta\nu_{1/2} = k N^{2/3}, \quad (\text{White, 1934}) \quad (38)$$

where k is a constant and N is the density of ions per cm^3 . This expression has been verified experimentally.

(See the review by Margenau and Watson, 1936) .

(iv) Collision Broadening

In the treatment of collision broadening two basic postulates are made, which assume a constant frequency perturbation and a finite radiation time. According to the Lorentz (1906) impact theory, which is of historical interest, an atom absorbs or emits a sharp frequency ν_0 during

the time between collisions. A collision completely stops the process of radiation, and the energy of the oscillating dipole is changed into kinetic energy.

By means of a Fourier analysis, the intensity distribution is found to be

$$I(\nu') = \frac{K}{(\nu' - \nu_0)^2 + \left(\frac{1}{2\pi\tau}\right)^2} \quad (39)$$

which has the same form as that of a natural spectral line.

τ is the mean time between collisions. By normalizing $I(\nu')$, the constant K is calculated to be $\frac{1}{2\pi^2\tau}$. The half-width of the line is

$$\Delta\nu_{\frac{1}{2}} = \frac{1}{\pi\tau} \quad (40)$$

$\frac{1}{\tau}$, the number of collisions per second, equals $\pi\epsilon^2\bar{v}n_1$, from kinetic theory, where $\bar{v}$ is the root-mean-square velocity of impact, n_1 , which may be found from the ideal gas law, is the number of atoms per unit volume and ϵ is the optical collision diameter. From kinetic gas theory,

$$\bar{v} = \left(\frac{8kT}{\pi\mu}\right)^{\frac{1}{2}} \quad (41)$$

where μ is the reduced mass of the colliding atoms. This gives a result for the half-width of:

$$\Delta\nu_{\frac{1}{2}} = \epsilon^2\bar{v}n_1 = \frac{4.70 \times 10^{12}}{c} \frac{\epsilon^2 P}{\sqrt{\mu T}} \text{ cm}^{-1} \quad (42)$$

where P is the gas pressure in torr and T is the temp-

erature in degrees K. All spectral lines are broadened to a greater extent by pressure of like atoms than by foreign atoms. The Lorentz theory implies that the broadening is caused by collisions of the second kind, which should be accompanied by a reduction in the total intensity of radiation which, in fact, does not occur.

Lenz (1924), and Kallmann and London (1929) retained the essentials of the Lorentz theory by giving ρ a new definition. Rather than assuming that the radiation process is stopped by the collisions, they suggested that a phase change takes place upon collision. They defined ρ as the distance of separation between two colliding atoms at which the phase of radiation undergoes a change of π . Weisskopf (1932) calculated

$$\rho \approx \left[\left(\frac{3\pi^2}{4} \right) \left(\frac{b}{\bar{v}} \right) \right]^{\frac{1}{5}} \quad (43)$$

when the perturber is a foreign atom, and

$$\rho \approx \left(\frac{4\pi B}{\bar{v}} \right)^{\frac{1}{2}} \quad (44)$$

when the perturber is a like atom. b is of the order of 10^{-32} or 10^{-31} cm.⁶ sec.⁻¹ while the Einstein B coefficient is equal to $\frac{e^2 f_{12}}{8\pi^2 m \nu_0}$. The substitution of Eqs. (43) and (44) into the Lorentz equation yields, for broadening by foreign

gases,

$$\Delta \nu_{\frac{1}{2}} \approx 2.2 b^{\frac{2}{5}} (\bar{\nu})^{\frac{3}{5}} n_1, \quad (45)$$

and for broadening by like atoms,

$$\Delta \nu_{\frac{1}{2}} \approx 4 \pi B n_1 \approx \left(\frac{e^2 f_{12}}{2 \pi m \nu_0} \right) n_1. \quad (46)$$

The results for $\mathcal{C}$, calculated from Eqs. (43) and (44), agree as to order of magnitude with values found by substituting experimental half-widths into $e^2 \bar{\nu} n_1$. However, there is poor agreement between the experimental values themselves.

(v) The Theory of Self-Absorption

When light is emitted from a source, it usually must travel through an absorbing layer of atoms or molecules before emerging to the outside. Self-reversal occurs if the resulting absorption is more pronounced at the centre of the spectral line than in the wings. In formulating a theoretical treatment of self-reversal, Cowan and Dieke (1948) assumed a frequency ν_0 at the centre of the spectral line and an intensity distribution $\mathcal{C}(\nu)$, such that $\mathcal{C}(\nu) d\nu$ was the energy radiated per unit volume in the interval $d\nu$. The radiation was assumed to travel with a velocity c in the $+x$ direction. According to their theory, the absorption in a given interval dx is proportional to $\mathcal{C}(\nu)$, and it also depends on the number of absorbing

atoms per unit volume. It follows that:

$$\frac{1}{c} \frac{d\mathcal{C}(\nu)}{dt} = \frac{d\mathcal{C}(\nu)}{dx} = -k P_a(\nu, x) \mathcal{C}(\nu), \quad (47)$$

where $P_a(\nu, x)$, which is normalized to unity, gives the shape of the absorption line and k is a constant. If the energy distribution in the incident light is constant over the absorption line width, then the radiation is absorbed at the rate :

$$\frac{dE}{dt} = -ck \int_0^\infty P_a(\nu, x) \mathcal{C} d\nu = -kc\mathcal{C} = -Bh\nu_0 n_a(x)\mathcal{C}, \quad (48)$$

where $\mathcal{C}$ is constant and independent of ν , B is the Einstein absorption coefficient and $n_a(x)$ is the density of the absorbing atoms.

The effective intensity distribution $I(\nu)$

in a self-reversed line is represented as follows:

$$I(\nu) = I_0 P(\nu) \int_0^\infty n_e(x) dx \exp. \left[-p \frac{P(\nu)}{P(\nu_0)} \right], \quad (49)$$

where I_0 is the peak intensity of the incident line, $n_e(x)$ is the density of the emitting atoms, P is the line profile and p , the absorption parameter, is represented by

$$\left(\frac{Bh\nu_0}{c} \right) P(\nu_0) \int n_a(x) dx. \quad (50)$$

If n_e is constant over the source, self-reversal does not occur. When true self-reversal occurs, the line shape has a definite minimum at ν_0 , with two maxima on either side,

which may be found by differentiating Eq. (49). In this case n_e is a maximum at some location in the source.

$$\text{At } \nu_0, \quad \frac{P(\nu)}{P(\nu_0)} = 1. \quad (51)$$

From Eq. (49),

$$I(\nu_0) = I_0 P(\nu_0) \int_0^\infty n_e(x) dx \exp.(-p). \quad (52)$$

$$\text{Maxima occur for } I(\nu) \text{ when } p \frac{P(\nu)}{P(\nu_0)} = 1. \quad (53)$$

Again, from Eq. (49)

$$I(\nu)_{\text{max}} = I_0 \frac{P(\nu_0)}{p} \int_0^\infty n_e(x) dx \exp.(-1). \quad (54)$$

Dividing Eqs. (54) and (56) gives

$$\frac{I(\nu)_{\text{max}}}{I(\nu_0)} = \frac{1}{p} (e^{-1}) (e^p) = \frac{e^{p-1}}{p}. \quad (55)$$

The separation of the two self-reversal maxima will depend on the shape of the incident line. If the incident line is Doppler broadened,

$$P(\nu) = \left(\frac{Mc^2}{2\pi RT\nu_0^2} \right)^{\frac{1}{2}} \exp. \left[\left(\frac{-Mc^2}{2RT\nu_0^2} \right) (\nu - \nu_0)^2 \right]. \quad (56)$$

Combining Eqs. (53) and (56) leads to

$$\left(\frac{\delta\nu}{\Delta\nu_{\frac{1}{2}}} \right)^2 = \frac{\ln p}{\ln 2}, \quad (57)$$

where $\delta\nu$ is the separation of the self-reversal maxima.

If the incident has a pure resonance shape due to radiation damping only,

$$p(\nu) = \frac{\frac{\delta}{2\pi}}{(\nu_0 - \nu)^2 + \left(\frac{\delta}{2}\right)^2} \quad (58)$$

combining Eqs. (53) and (58) yields

$$\left(\frac{\delta\nu}{\Delta\nu_{1/2}}\right)^2 = p - 1. \quad (59)$$

For either Doppler or resonance broadening, a value of p may be found for which the original half-width is equal to the separation of the maxima of the self-reversed line,

$$\frac{\delta\nu}{\Delta\nu_{1/2}} = 1. \quad (60)$$

In both cases this occurs for $p = 2$, and

$$\frac{I(\nu)_{\max}}{I(\nu_0)} = \frac{e^{p-1}}{p} = \frac{e}{2} = 1.36. \quad (61)$$

If the half-width of the incident line is constant with pressure, then, for a Doppler-broadened incident line, a plot of $(\delta\nu)^2$ against p will be logarithmic, whereas for a radiation-damped incident line a plot of $(\delta\nu)^2$ against p will be linear.

CHAPTER IV

DESCRIPTION OF THE APPARATUS

The apparatus is shown schematically in Fig. (1). Light from a spectral lamp is passed through lenses L_1 and L_2 and the diaphragm DV , and the resulting parallel beam is made incident on the Fabry-Perot etalon in the pressure tank. Filters F_1 and F_2 are used to select a specific spectral line for study. The light from the fringes is focussed by lens L_3 on the pinhole P , the image of which is focussed by lens L_4 on the cathode of the photomultiplier. The signal from the photomultiplier is amplified by the picoammeter and is registered with a strip chart recorder. The entire optical system is mounted on an optical bench.

A) Cesium Vapour Lamps

(1) The Osram Lamp

An Osram a.c. discharge lamp consists of a glass bulb containing two electrodes, a small quantity of an alkali metal and an inert gas at low pressure. The central bulb is surrounded by an outer glass mantle that serves both as a protective device and as a shield against the loss of heat. The manufacturer specifies, for the cesium lamp, an operating current of 1.5 amperes at 8 volts. The starting voltage for

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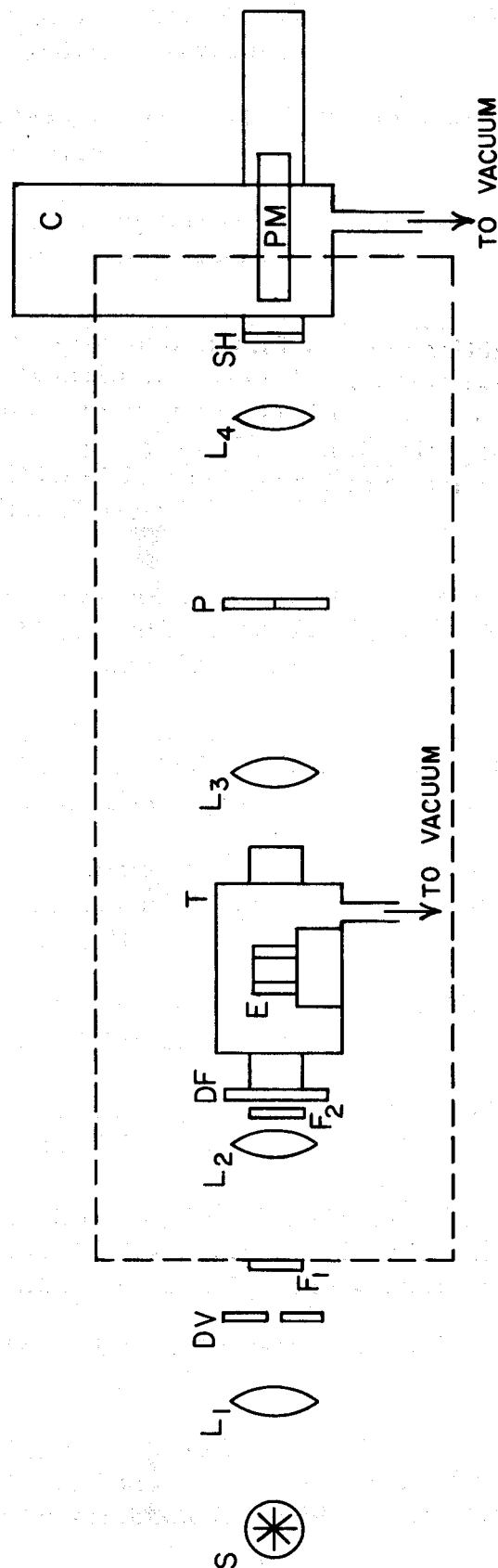


Fig. (1) A schematic diagram of the Fabry-Perot Scanning Interferometer. DV and DF are variable and fixed diaphragms, F_1 and F_2 are glass and interference filters, respectively, L_{1-4} are lenses, T is the tank, E - etalon, P - pinhole, S - source, SH - shutter, C - cryostat, PM - photomultiplier. The dotted line represents the light-proof shield.

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the lamp is, however, 200 volts.

(ii) The Radio Frequency Lamp

This type of electrodeless rf. lamp was described by Atkinson, Chapman, and Krause (1965) . It consists of a pyrex glass cylinder containing a small quantity of cesium metal and argon at low pressure which serves to carry the discharge. The bulb was mounted in a coil which formed part of a tank circuit of the power oscillator shown schematically in Fig. (2). The upper 6 cm. length of the bulb had a diameter of 1.8 cm., while the bottom 3 cm. had a diameter of 0.9 cm. The thickness of the glass wall was approximately 2 mm. The discharge took place primarily in the upper section of the lamp, while the narrower base served as a reservoir for the cesium and, during the operation of the lamp, rested in a heater block whose temperature controlled the vapour pressure of the cesium. The lamps contained between 0.1 g. and 0.5 g. of cesium, and argon at pressures varying from 0.5 mm. to 10 mm. Hg.

The oscillator, whose circuit is shown in Fig. (2), operated at a frequency of approximately 70 Mc. The power dissipation increased with the cesium vapour pressure, as the impedance became smaller. The power dissipation could be

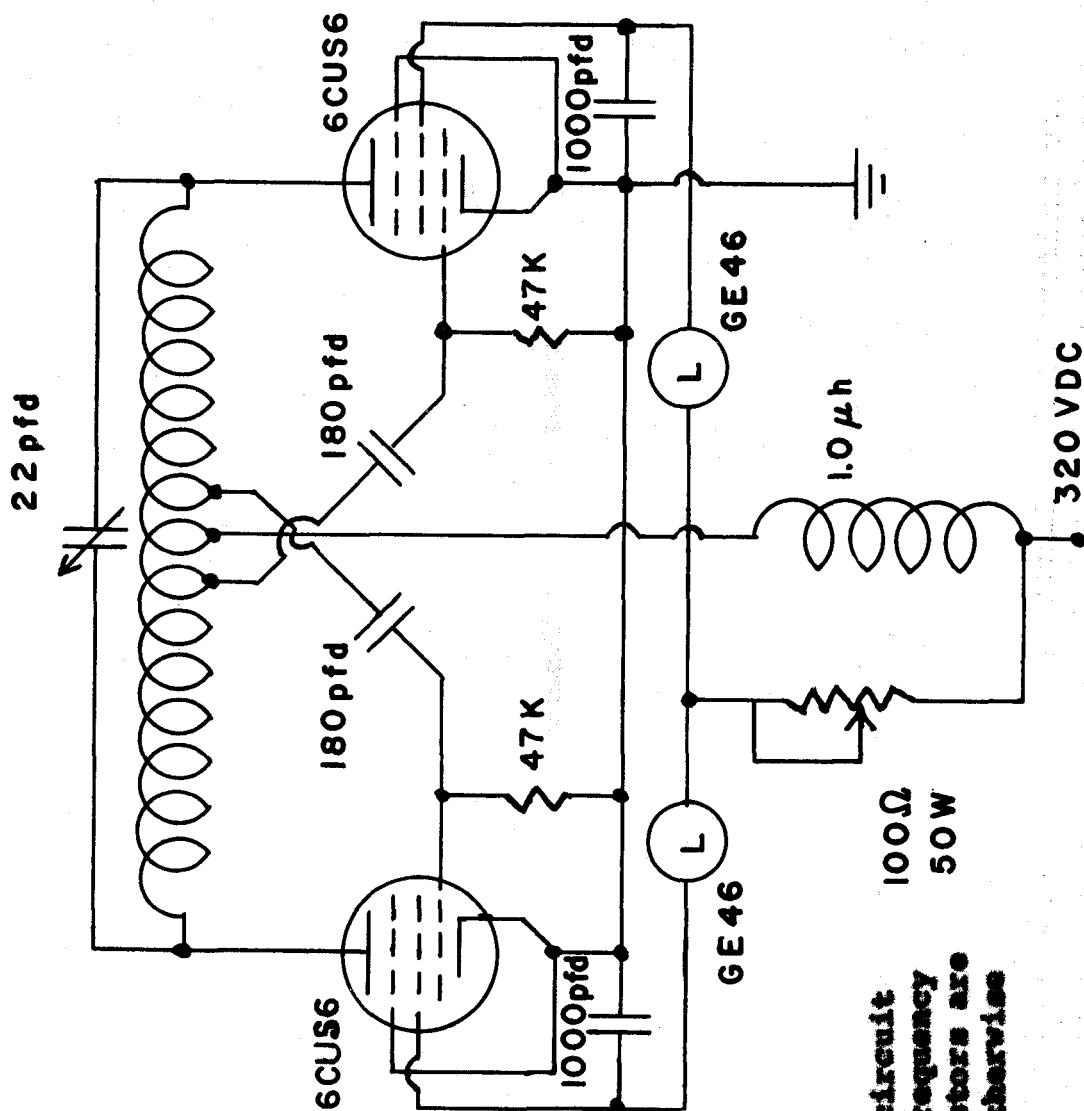


Fig. (2) The oscillator circuit for the radio-frequency lamp. All resistors are 2 watt unless otherwise specified.

controlled by varying the screen grid currents by means of the 10K rheostat. A Lambda Voltage Regulated Power Supply provided the operating voltage of 320 volts, with a current of 220 milliamps.

The heater block was located in one corner of the oscillator chassis, immediately beneath the coil. It consisted of a copper cylinder of 0.5 inches O.D., around which was wrapped a length of No. 28 chromel resistance wire, having a resistance of 7 ohms., insulated by porcelain beads and sealed in a block of asbestos with Johns-Manville No. 20 Refractory Cement.

The temperature of the lamp was measured with a chromel-alumel thermocouple placed in contact with the bulb base. The copper cylinder heated the base of the lamp uniformly, and hot spots, found when the heating coil was wrapped directly around the lamp base, did not occur.

B) The Interferometer

The Fabry-Perot etalon consisted of two circular quartz plates, held in a Hilger mount, with the plane surfaces of each plate making an angle of several minutes (up to a maximum of 30) with each other. The plane sides facing one another were polished flat (to within 0.01 wave -

length of green light) and were silvered. The plates were separated and held parallel by a quartz spacer with three projecting studs at each end. The spacer was so constructed that the stud surfaces, after being ground, formed an almost perfectly parallel plane. The plates were held in place by a brass flange at one end, and three spring-loaded clamps at the other, which kept them tightly against the spacer. True parallelism with respect to the inner surfaces of the plates was obtained by means of fine spring-loaded adjusting screws that altered the tension at three points on one of the plates.

The optical arrangement is illustrated in Fig. (1). Light from the source was focussed by lens L_1 on the variable diaphragm DV, which had an opening of approximately 1 cm. This diaphragm, located at the focus of the achromat L_2 , acted as a virtual source and the light from it was collimated, passed through the window of the pressure tank and made incident on the Fabry-Perot etalon. The fixed diaphragm, with an opening of 2 cm., restricted the illumination to the centre of the Fabry-Perot plates and thus the effect of non-parallelism in the plates, if present, was reduced to a minimum. The light from the fringes, after passing through the exit window of the tank, was focussed by the achromat L_3 on the pinhole, which permitted light originating only from

the central fringe to pass through. This was then focussed on the photocathode of the photomultiplier by lens L_4 . The pinhole diameter, which, in this experiment equalled 0.01 cm., was governed by several factors. For optimum resolution it had to be small compared with the dimensions of a fringe, and yet large enough to admit sufficient light to the photomultiplier tube. (Jarrett, 1962)

The optical system was covered with a light proof shield which consisted of tar paper and three layers of black cloth.

Two spectral filters were used to separate the two components of the cesium doublet. A Jena RG5 glass filter blocked the part of the spectrum from the ultraviolet to $6500 \text{ \AA}$. Two interchangeable Schott Interference filters were used in conjunction with the Jena filter so that either the $8943 \text{ \AA}$ or the $8521 \text{ \AA}$ line could be studied separately.

The cylindrical brass tank used to house the etalon was fitted with an air inlet valve and an Autovac gauge head for pressure measurements. The flat top of the tank was held in place by eight bolts.

Fig. (3) shows the layout of the valves in the vacuum system of the tank which could be evacuated with the roughing pump by closing valve C and opening Valves A and B. Valves

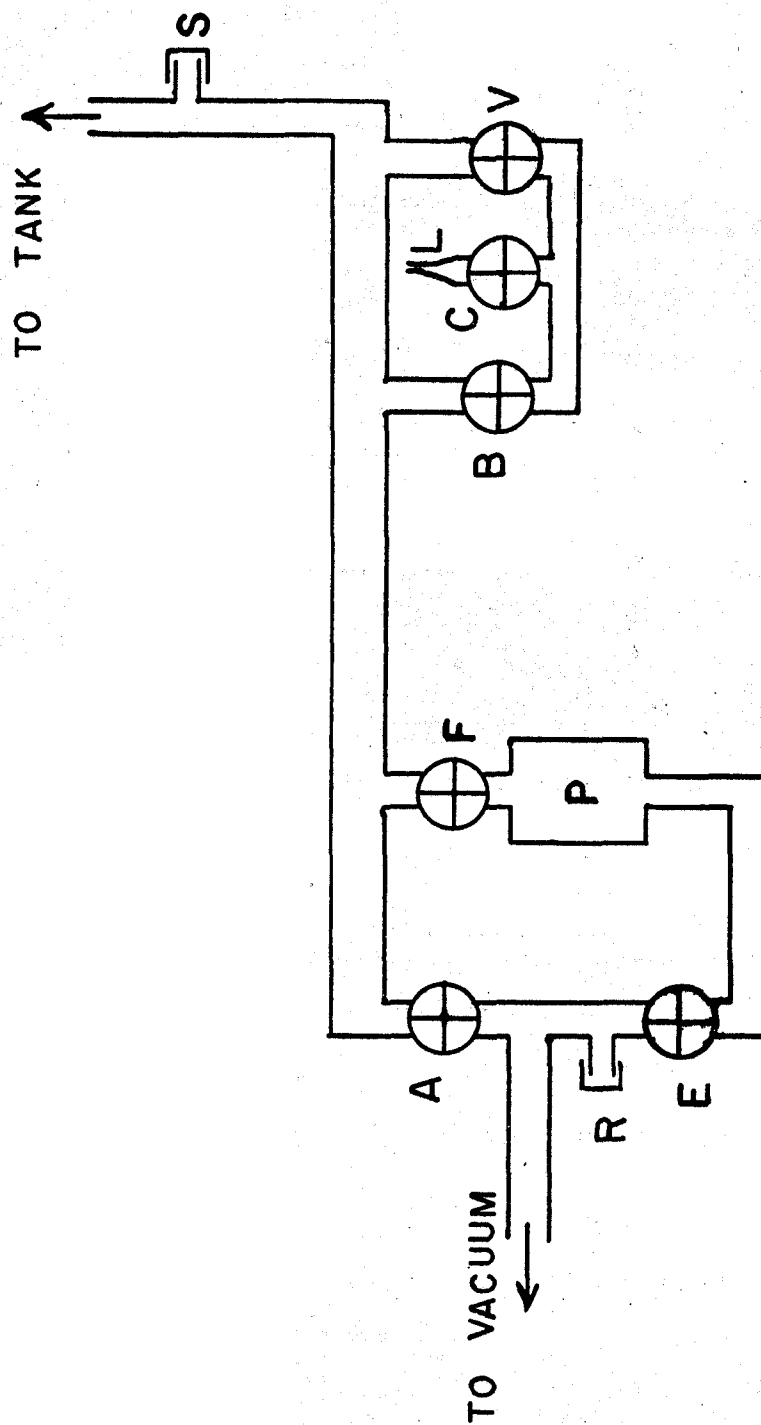


Fig. (3) A schematic diagram of the vacuum system for the scanning interferometer. A, B, C, E, F are speedivalves, R and S are air admittance valves, V is a variable leak valve, P is the oil diffusion pump, and L is the glass capillary leak.

E and F controlled the operation of the oil diffusion pump which was only used to achieve a high vacuum for purposes of calibrating the Autovac gauge. Closing valves A and B and opening C isolated the forepump from the tank and permitted air to leak in slowly through a drawn glass capillary containing a glass-wool filter. The refractive index changed linearly with pressure, so that the ring system expanded continuously outward and the growth and decay of the central fringe could be detected by the photomultiplier tube.

C) The Light Detection and Recording System

The light originating from the interference fringes was detected by an ITT FW 1186 photomultiplier tube which was cooled with liquid air. As is shown schematically in Fig. (4), the tube was operated at a potential of 1600 volts supplied by a Fluke H.T. Power Supply. The output of the P.M. tube was amplified by a Keithley picoammeter and registered with a Bausch and Lomb strip chart recorder which was matched to the picoammeter by a 100Ω potentiometer.

A vacuum was maintained in the photomultiplier cryostat by means of an oil diffusion pump backed with a mechanical forepump. An autovac head was mounted immediately above the photomultiplier tube to monitor the quality of the vacuum.

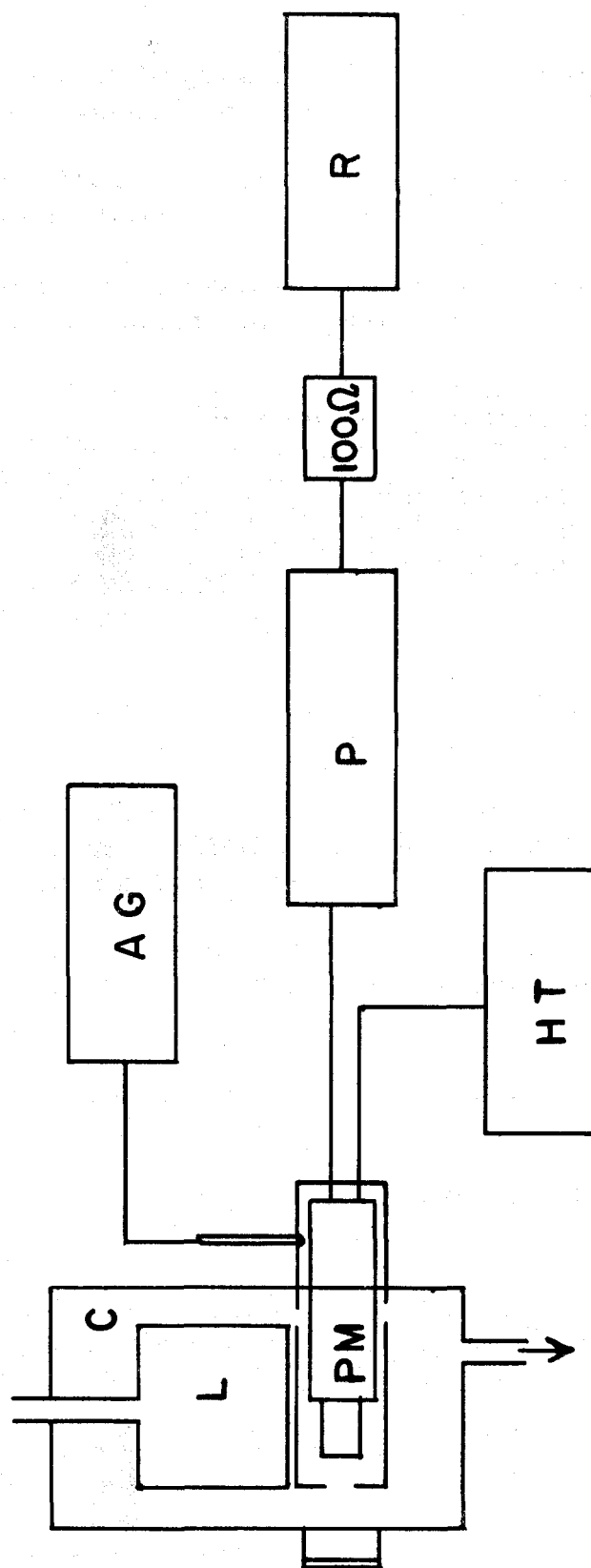


Fig. (4) A block diagram of the Light Detection and Recording System. AG-- Autovac gauge, P - preamplifier, R - strip chart recorder, HT - high voltage power supply, PM - photomultiplier, L - liquid air reservoir, C - cryostat.

D) Apparatus for Measuring Fluorescent Intensities

In order to assess the ability of the spectral lamps to excite resonance fluorescence, advantage was taken of another experiment which was concerned with cesium fluorescence. In testing the lamps, the emitted light was separated into the two f.s. components with a monochromator and was made incident on a fluorescence cell containing cesium vapour at constant temperature. The resulting resonance fluorescence was detected with a cooled photomultiplier tube and was registered with an electrometer and a strip chart recorder as a function of the lamp parameters.

CHAPTER V

EXPERIMENTAL PROCEDURE

A) Preliminary Adjustment of the Interferometer

A sodium Ceram lamp was placed on the optical bench in front of the interferometer and as far away as possible from the photomultiplier. The variable diaphragm DV was placed half-way between the lamp and the tank, and lens L_1 was adjusted to produce an image of the lamp on the diaphragm DV . Lens L_2 was then placed on the opposite side of the diaphragm DV at a distance equal to its focal length, permitting parallel light to enter the entrance window of the tank.

The etalon was then set on the mount in the tank, which was adjusted to permit the light from the source to illuminate the plates. The fringes were viewed through the exit window of the tank and the plates were adjusted for parallelism. The eye was moved horizontally and vertically, and the fringes were said to be in focus if the spacing between the rings did not change. The adjusting screws were tightened in the direction in which the rings expanded, and loosened in the direction in which the rings contracted.

The pinhole was then located roughly half-way between the etalon and the photomultiplier. Lens L_3 was moved so that an image of the fringes was formed on the frame on the pinhole, which was then adjusted until the image of the central fringe coincided with the pinhole itself. Since the pinhole was recessed approximately 2 mm. in its frame, a tiny piece of paper was placed in the recess flat against the pinhole, as a screen on which the fringe system was viewed. Final adjustments were made with lens L_3 by inspecting the image with a magnifying glass. The system was then covered with a black cloth except for a small access port near the cryostat. All lamps were turned off except a desk lamp which illuminated the face of the picoammeter. Lens L_4 was next adjusted to focus the bright image of the pinhole on the cathode of the photomultiplier. A maximum reading on the picoammeter corresponded to the proper position of the lens. In order to obtain the correct height for the source, the lamp holder was moved slightly in the vertical plane until a maximum signal was obtained. A similar procedure was used for the rf. lamp. It was found necessary to separate two turns of the coil to prevent some of the light from being obscured. After the completion of these adjustments the shutter was closed and the top of the tank placed in position.

Only the forepump was used to evacuate the tank during actual experiments, with the oil diffusion pump disconnected from the system by valves E and F. During the evacuation, valves A and B were opened and C was closed. In order to allow the air to leak slowly into the evacuated tank through the glass capillary leak, valves A and B were quickly and simultaneously closed and C was opened immediately. The pressure rose from 50μ to one atmosphere in approximately 90 minutes. The oil diffusion pump, which was used to produce a high vacuum needed for the calibration of the Autovac gauge, was connected to the system by closing valve A and opening valves E and F.

B) Determination of Spectral Line Shapes

With the overhead lights off and the light-proof shield in place, the etalon tank was evacuated. Air was next allowed to leak into the tank, causing the index of refraction to change, while the changing illumination of the pinhole, caused by the expanding fringes, was monitored by the photomultiplier tube. A dark current of 1×10^{-12} amps. was obtained with the photomultiplier cooled by liquid air. The photomultiplier signal, amplified by the picoammeter, produced a trace of light intensity against time on the strip

chart recorder. A linearity of 1.5% in the variation of the refractive index with time over the first order was obtained using the glass capillary leak. Using the 5.50 mm. spacer, three orders were recorded over a period of 63 minutes, while with the 8.60 mm. spacer, four orders were scanned in 56 minutes. It was found convenient to use a chart speed of 0.20 inches / min.

After each change in the operating conditions of a lamp a period of time was allowed to elapse until the lamp discharge again became stabilized. With the tank evacuated and the refractive index between the mirrors held constant, a steady state was indicated by a constant picometer signal.

CHAPTER VI

DISCUSSION OF THE RESULTS

(A) Intensities of the Resonance Lines

The intensities of the resonance lines emitted by the lamps were determined by using them to excite fluorescence in cesium vapour at a constant low pressure. The fluorescent light was observed at 90° to the direction of excitation and its intensity was recorded by means of a cooled photomultiplier followed by an electrometer and a strip chart recorder.

The results for both resonance lines $8943 \text{ \AA}$ and $8521 \text{ \AA}$, emitted by the Osram lamp, are recorded in Table (1) and are represented in Fig. (5) which shows plots of the fluorescent intensity against lamp current. The two curves have been arbitrarily adjusted to a common peak intensity and the variation of the intensity ratio is also shown. Both the $8943 \text{ \AA}$ and the $8521 \text{ \AA}$ lines reach a maximum intensity at 0.5 amps, which decreases rapidly to a steady low value at 2.2 amps. This may be explained by the fact that, as the lamp current increases, the vapour pressure of the cesium also increases producing a progressively more self-reversed line with correspondingly

Table (1)

Resonance Fluorescent Intensities of Resonance

Lines excited by the Cesium Osram Lamp .

All intensities are given in arbitrary units .

Lamp Current (Amps)	I (8521)	I (8943)	$\frac{I (8521)}{I (8943)}$
0.3	6.3	7.3	0.86
0.5	8.5	11	0.77
0.6	7.5	10	0.72
0.7	6.2	9.0	0.68
0.8	5.3	8.0	0.66
0.9	4.0	6.0	0.66
1.0	3.1	5.0	0.62
1.1	2.2	3.4	0.64
1.2	1.7	2.7	0.62
1.3	1.2	1.9	0.63
1.4	0.85	1.4	0.60
1.5	0.65	1.2	0.56
1.7	0.43	0.76	0.51
2.0	0.26	0.50	0.52
2.2	0.26	0.50	0.52

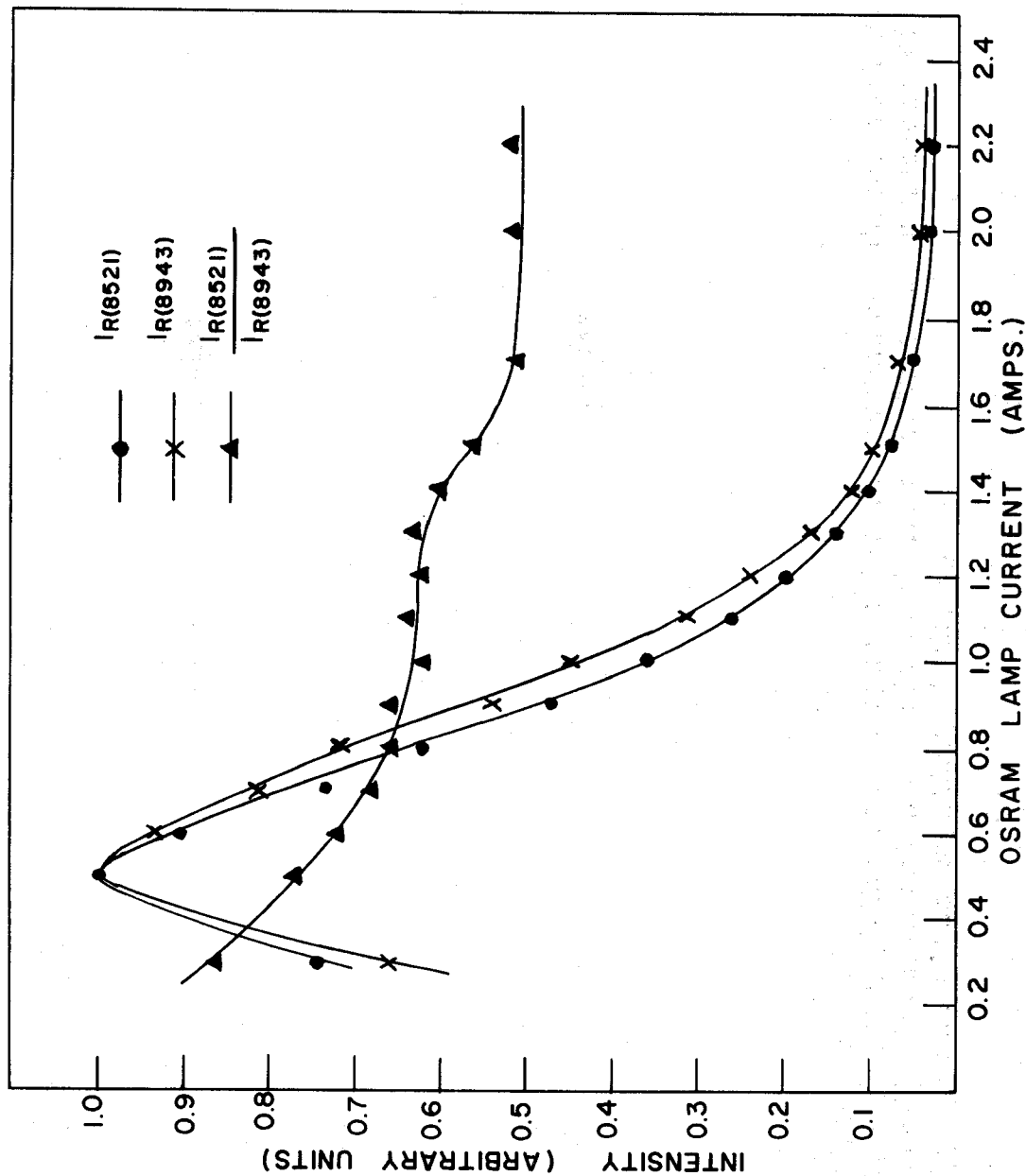


Fig. (5) Resonance Fluorescent Intensities of the 8521 Å and 8943 Å components excited with an Osram lamp as functions of the lamp current. The two curves have been arbitrarily adjusted to show the same peak intensities. The variation of the intensity ratio is also shown.

less intensity available for the excitation of the fluorescence. The ratio of the intensities, $\frac{I(8521)}{I(8943)}$, falls slowly from a maximum of 0.86 at 0.3 amps to a minimum of 0.51 at 1.7 amps. The intensities of the two components, 8521 Å and 8943 Å, should be in the ratio of the statistical weights of the excited states $^2P_{3/2} : ^2P_{1/2}$, or 4:2. Since this value is never reached experimentally, it must be assumed that self-absorption is affecting each line to a different degree. Tables (2), (3), (4), and (5), and Figs. (6) and (7) show similar plots for the 8943 Å and 8521 Å components respectively emitted by the rf. lamps. A series of these was prepared, each containing the carrier gas (argon) at a different pressure. The fluorescent intensity produced by the lamp was studied as a function of the lamp temperature and it may be seen that, as the pressure of argon decreased, the intensity of both resonance lines, 8943 Å and 8521 Å, increased. The maximum intensities also occurred at decreasing temperatures for increasing pressures of argon. For both resonance lines at pressures of 0.5 torr, 1.0 torr, and 3 torr of argon, the intensity curves fell rapidly as the temperature was increased to 160 °C. The curves for 10 torr of argon fell more slowly, following closely the intensity curves

Table (2)

Resonance Fluorescent Intensities of Resonance

Lines excited by the Cesium Radiofrequency

Lamp at an argon pressure of 0.5 torr .

All intensities are given in arbitrary units .

Temperature (°C)	I (8521)	I (8943)	$\frac{I (8521)}{I (8943)}$
86.0	64	42	1.50
102	57	46	1.24
109	40	38	1.05
116	20	21	0.95
128	4.8	5.2	0.92
134	2.8	3.2	0.87
148	1.1	1.3	0.84
157	0.63	0.78	0.81

Table (3)

Resonance Fluorescent Intensities of Resonance**Lines excited by the Cesium Radiofrequency****Lamp at an argon pressure of 1.0 torr .****All intensities are given in arbitrary units .**

Temperature (°C)	I (8521)	I (8943)	$\frac{I (8521)}{I (8943)}$
80.0	48.4	35.0	1.40
87.0	48.4	28.5	1.26
94.0	46.6	42.3	1.10
99.0	42.2	40.0	1.05
107	30.0	31.0	0.97
113	21.0	22.0	0.95
122	7.65	8.47	0.87
132	2.81	3.30	0.85
141	1.23	1.54	0.80
153	0.56	0.680	0.82
166	0.326	0.410	0.79

Table (4)

Resonance Fluorescent Intensities of Resonance

Lines excited by the Cesium Radiofrequency

Lamp at an argon pressure of 3 torr .

All intensities are given in arbitrary units .

Temperature (°C)	I (8521)	I (8943)	$\frac{I (8521)}{I (8943)}$
64.0	26.4	27.5	0.96
68.0	37.0	34.1	1.08
73.0	34.8	33.0	1.06
85.5	33.0	3.30	1.00
92.0	24.6	26.4	0.93
98.0	19.3	21.0	0.91
105	13.0	14.3	0.90
114	6.77	7.60	0.89
131	1.94	2.30	0.84
142	0.88	1.10	0.80
165	0.34	0.43	0.80

Table (5)

Resonance Fluorescent Intensities of Resonance

Lines excited by the Cesium Radiofrequency

Lamp at an argon pressure of 10 torr .

All intensities are given in arbitrary units .

Temperature (°C)	I (8521)	I (8943)	$\frac{I (8521)}{I (8943)}$
66	14.0	15.4	0.91
75	8.80	9.95	0.88
91	5.90	6.80	0.86
103	4.10	4.85	0.85
122	2.16	2.60	0.83
139	0.97	1.20	0.87
158	0.44	0.55	0.80

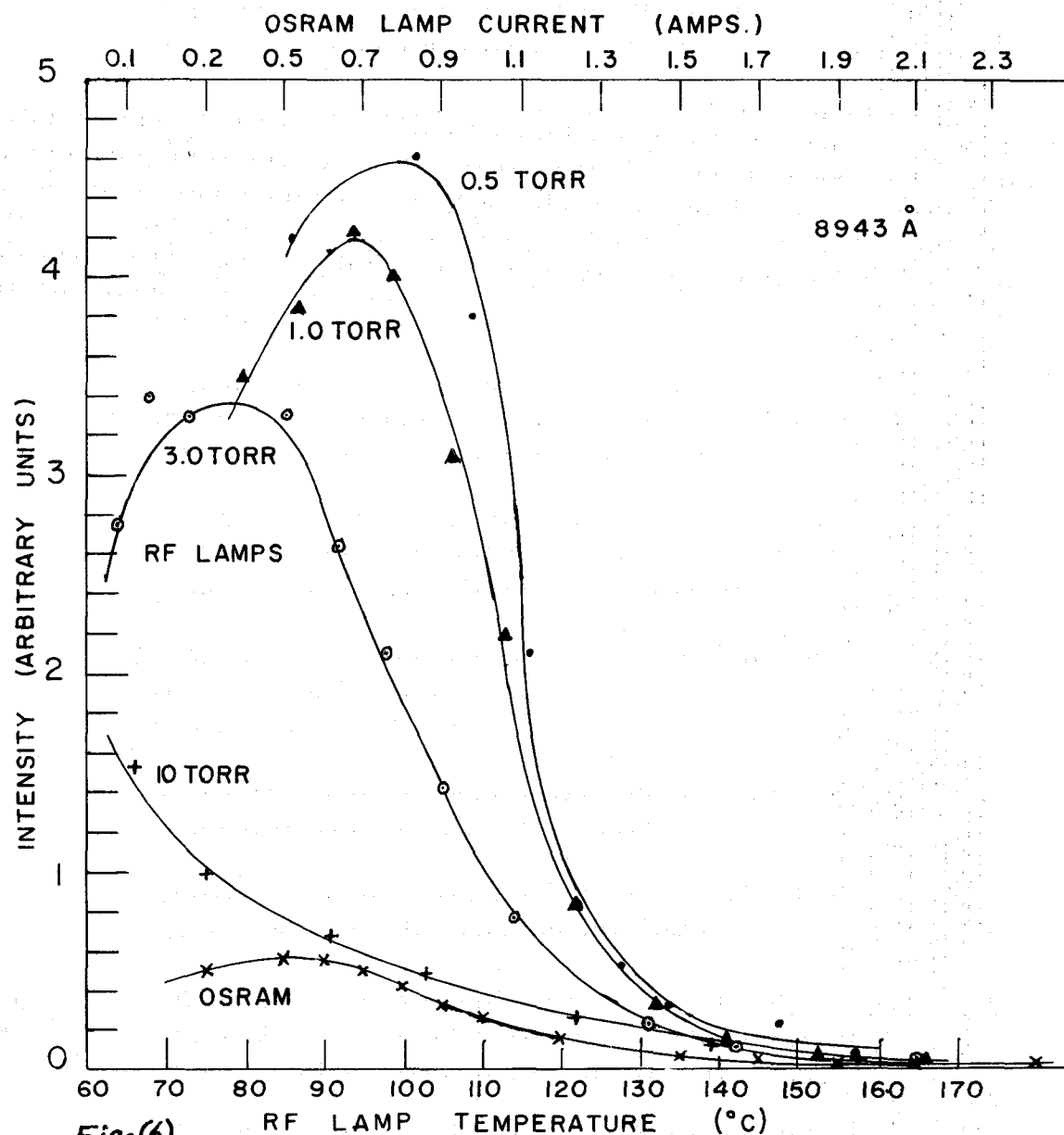


Fig-(6) Resonance Fluorescent Intensities of the 8943 Å line excited with the rf. lamp as functions of the lamp temperature. Pressures are those of the lamp carrier gas, argon. A comparison with the corresponding line excited with the Osram lamp is also shown.

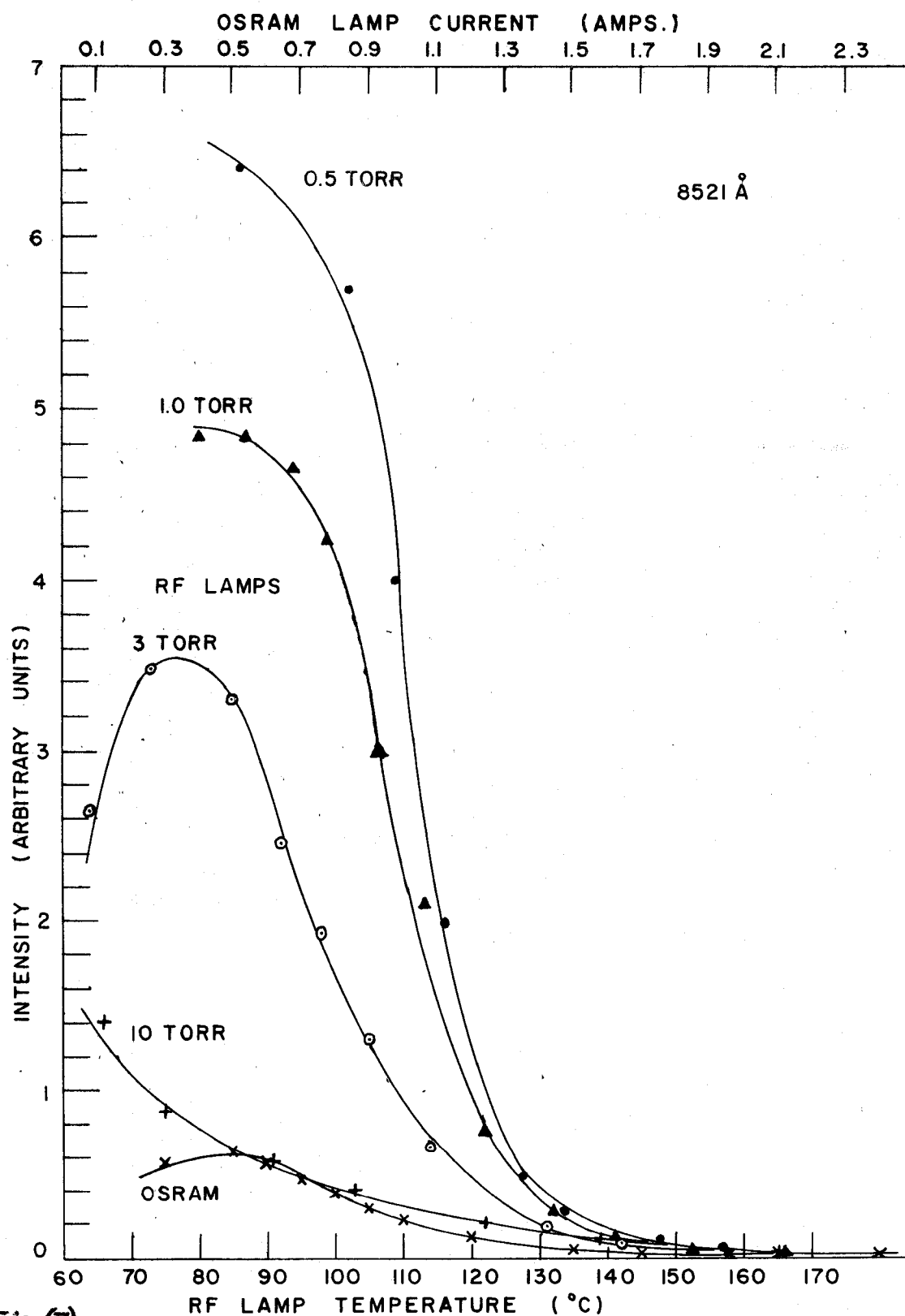


Fig. (7)

Resonance Fluorescent Intensities of the 8521 Å line excited with the rf. lamp as functions of the lamp temperature. Pressures are those of the lamp carrier gas, argon. A comparison with the corresponding line excited with the Osram lamp is also shown.

for the Osram lines which were plotted on the same graph for the sake of comparison.

The shape of the intensity curves may be explained as follows. The smaller the pressure of the carrier gas, the smaller should be the effect of pressure broadening. In the case of the lamp containing 1 torr of argon, as the lamp temperature rose from 60°C to 95°C, the vapour pressure increased and the number of possible emitters also increased, with a comparable gain in intensity. However, as the temperature and vapour pressure continued to rise, collision broadening and self-reversal rapidly became important factors determining the shapes of the spectral lines. This becomes quite apparent from the traces of the spectral lines shown in Figs. (9) and (10). It would seem that the most efficient light sources are those with a minimal pressure of the carrier gas and the production of a satisfactory light source is a matter of compromise between an argon pressure as low as possible and yet high enough to start and maintain a stable discharge.

The intensity ratios $\frac{I(8521)}{I(8943)}$ for the rf. lamps, plotted in Fig. (8), also show a marked dependence on the pressure of the carrier gas. All the curves of $\frac{I(8521)}{I(8943)}$

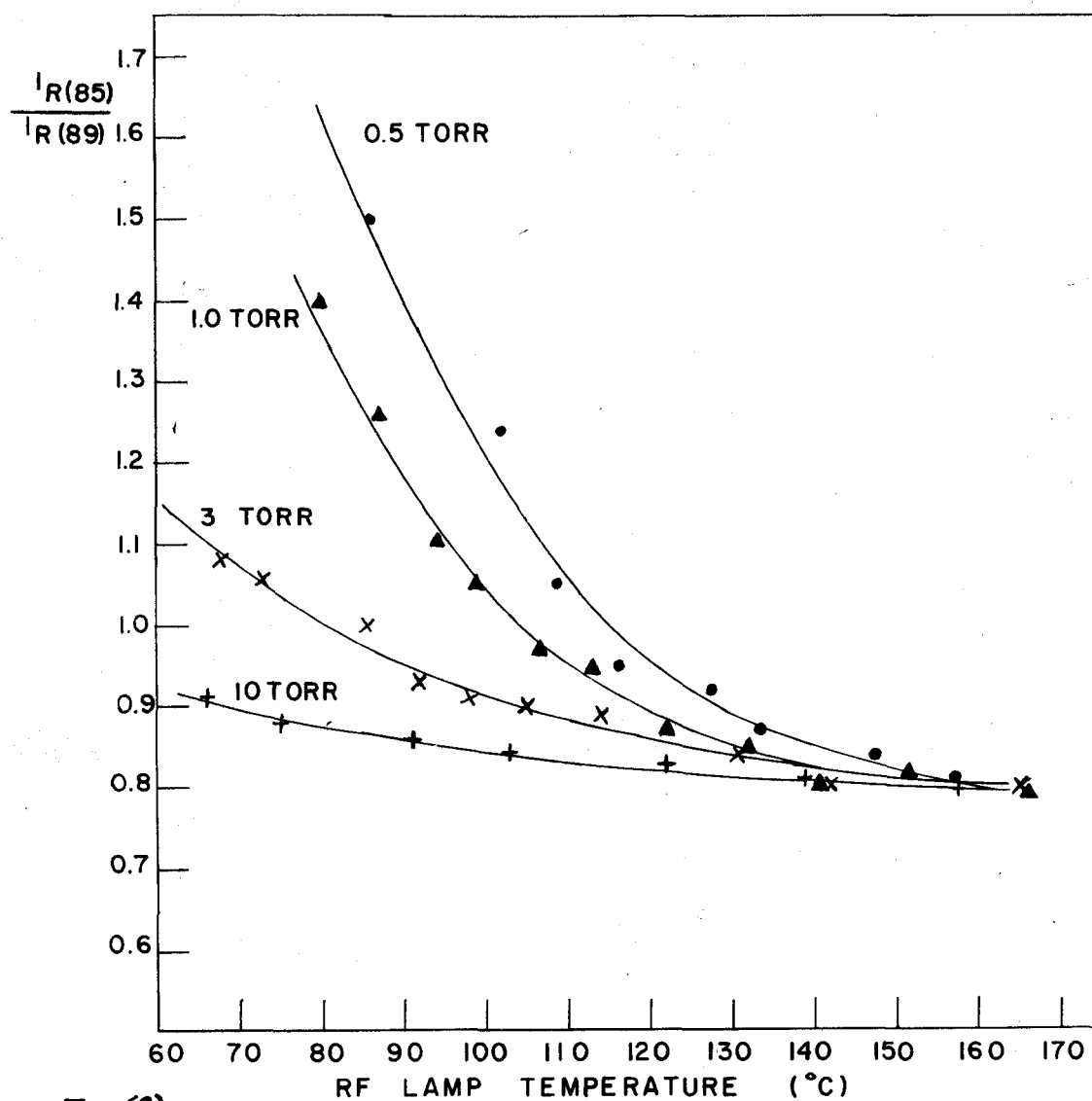


Fig. (8)
Ratios of Resonance Fluorescent Intensities of the 8521 Å and 8943 Å components excited with the rf. lamp. Pressures are those of the lamp carrier gas, argon.

approach the lowest value of 0.8 at the operating temperature of 165°C . The theoretical intensity ratio 4:2 was most closely approached at an argon pressure of 0.5 torr and a temperature of 85°C . The ratio then decreased with decreasing argon pressure to a value of 0.91 at 65°C . Again, this would indicate the presence of self-absorption in the lamp, which increases not only with increasing cesium vapour pressure but also with the pressure of the carrier gas.

(B) Half-Widths of the Resonance Lines

The half-widths of the resonance lines were obtained by direct measurement of the interferograms. The distance between the maxima in the interferograms, arising from the same spectral component, was assumed equal to the spectral range. This distance in wave numbers was equal to one-half the reciprocal of the etalon spacer thickness. For example, for the cesium rf. lamp, the spacer measured 0.860 cm., and the spectral range therefore was 0.581 cm^{-1} . For the cesium Oxram lamps, with a 0.550 cm. spacer, the spectral range was 0.909 cm^{-1} . Thus the half-width was determined by taking the ratio of the half-width of the interferogram peak to the measured spectral range and mult-

implying it by the spectral range in wave numbers. Three scans of the resonance lines, $8943 \text{ \AA}$ and $8521 \text{ \AA}$, for both the rf. and the Osram lamps, were taken at each value of the operating parameters. For example, in the case of the $8943 \text{ \AA}$ line, with a chart speed of 0.20 inches / minute, three orders were recorded over a period of 63 minutes using the 5.50 mm. spacer, while with the 8.60 mm. spacer, four orders were scanned in 56 minutes.

Typical interferogram traces are shown in Figs. (9) and (10). In one order there are two main maxima caused by the h.f.s. splitting of the ground state. Each maximum, in turn, consists of two smaller peaks produced by the h.f.s. splitting of the P states. As the current increases in the Osram lamps, the self-reversal and width of the lines both increase rapidly, so that the lines and the orders merge with one another, with only the self-reversal minima being readily identified. As the temperature of the metal increases in the rf. lamps, the lines become broader and more self-reversed, and, in the case of the $8943 \text{ \AA}$ components, at high temperatures three peaks appear in each maximum arising from the ground state h.f.s. splitting.

The optically allowed transitions and their relative

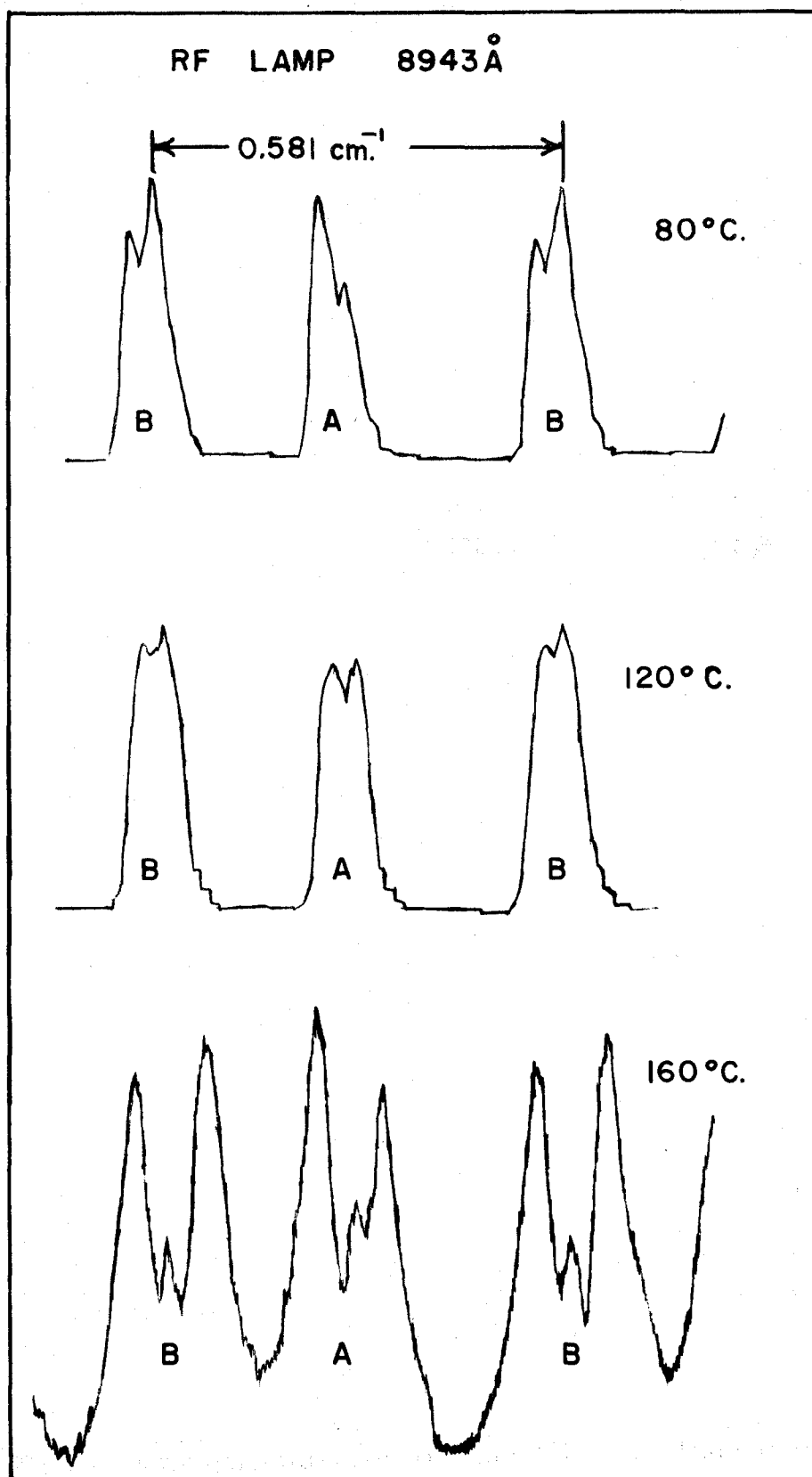


Fig. (9)
**Typical Interferogram Traces of the 8943 Å line emitted by the
 rf. lamp. Spectral Range : 0.581 cm⁻¹**

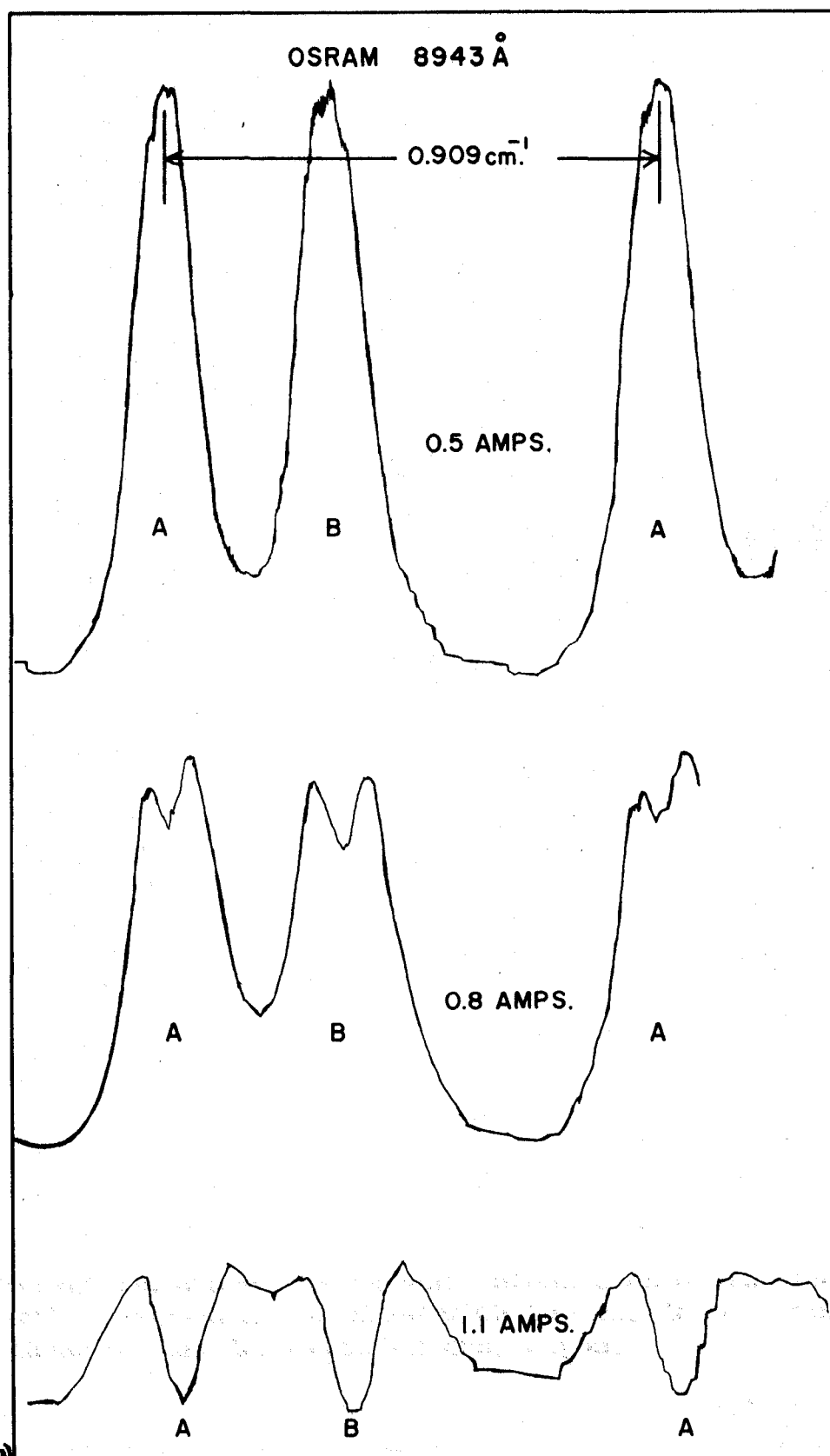


Fig. (10)

Typical Interferogram Traces of the 8943 Å Line emitted by the Osram lamp. Spectral Range : 0.909 cm⁻¹

intensities are presented in Figs. (11a) and 11B). The transitions $^2P_{3/2} \rightarrow ^2S_{1/2}$ ($F = 4, 3, 2, \rightarrow F=3$) and $^2P_{1/2} \rightarrow ^2S_{1/2}$ ($F = 4, 3, \rightarrow F=3$) are referred to as the A components of the 8521 Å and 8943 Å lines respectively. Similarly, the transitions $^2P_{3/2} \rightarrow ^2S_{1/2}$ ($F=5, 4, 3 \rightarrow F=4$) and $^2P_{1/2} \rightarrow ^2S_{1/2}$ ($F=4, 3 \rightarrow F=4$) are called the respective B components of the 8521 Å and 8943 Å lines.

The half-widths of the A and B components of the 8521 Å and 8943 Å lines emitted by the Osram lamp were considerably larger than those produced by the rf. lamps. They are listed in Tables (6) and (7) and are plotted against operating current in Figs. (12) and (13). The corresponding separation of the self-reversal peaks are also given in Tables (6) and (7) and are plotted in Figs. (12) and (13).

The half-width of the entire 8521 Å line ranged from 0.450 cm.⁻¹ at 0.5 amps to 0.706 cm.⁻¹ at 1.0 amp. At higher currents, the line became broader than the spectral range of the instrument and its half-width could no longer be measured. The half-widths of the components A and B varied from 0.154 cm.⁻¹ and 0.171 cm.⁻¹, respectively, at 0.5 amps, to 0.275 cm.⁻¹ and 0.316 cm.⁻¹ at 0.8 amps. Again, beyond this point, the two components merged and could no

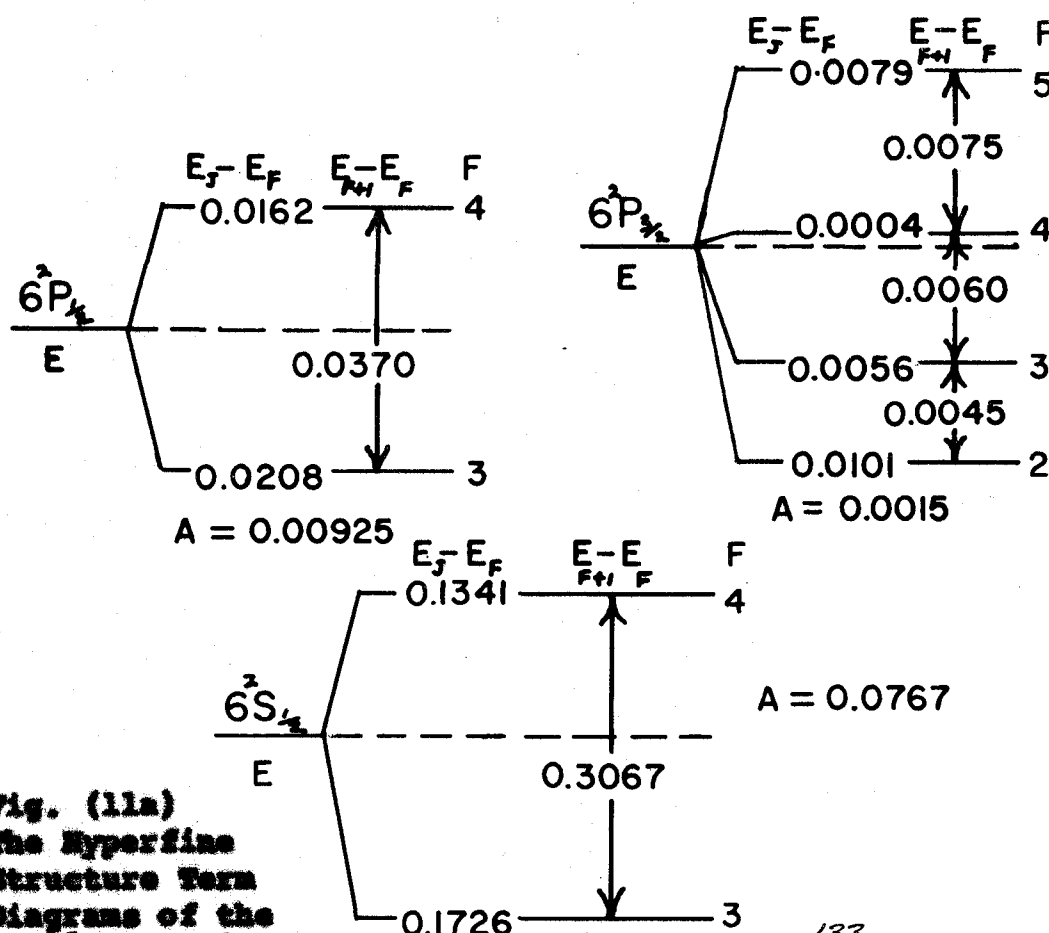
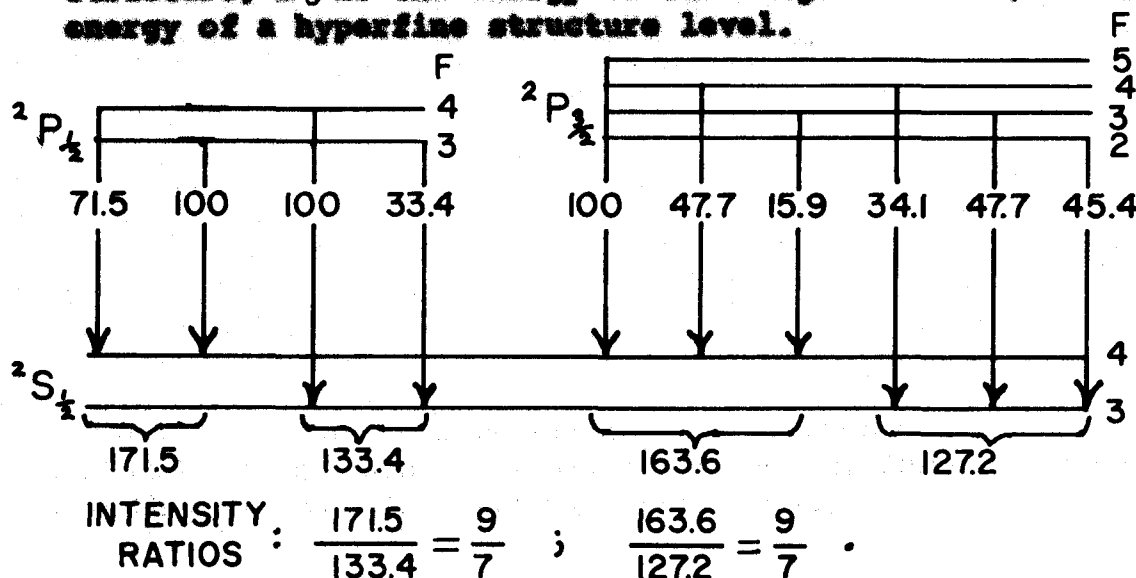


Fig. (11a)

The Hyperfine
Structure Term
Diagrams of the
 $^2S_{1/2}$, $^2P_{1/2}$, and $^2P_{3/2}$

Energy Levels of Cesium¹³³. All Separations are in units of cm.⁻¹ A is the interval factor for hyperfine structure, E_J is the energy of the original level, and E_F is the energy of a hyperfine structure level.



(11b) Optically Allowed Transitions and Their Relative Intensities. Intensity Ratios of Components due to Ground State Splitting are also shown. References for the hyperfine structure interval factors, A: 0.0015, Goudsmit (1933) and Høpfner and Kruger (1936); 0.00925, 0.0767, Granath and Stranathan (1933).

Table (6)

Half-Widths and Separations of the Self-Reversal
 Maxima in the Cesium 8521 Å Component emitted
 by the Osram Lamp

Current (amps)	Half-Width (cm. ⁻¹)			Separation of Maxima (cm. ⁻¹)	
	Entire	Component A	Component B	Component A	Component B
0.5	0.450	0.154	0.171	0.061	0.067
0.6	0.486	0.195	0.208	0.071	0.076
0.7	0.516	0.246	0.258	0.087	0.092
0.8	0.591	0.275	0.316	0.097	0.108
0.9	0.670	-----	-----	0.109	0.125
1.0	0.706	-----	-----	0.117	0.131

Table (7)
Half-Widths and Separations of the Self-Reversal
Maxima in the Cesium 8943 Å Component emitted
by the Osram Lamp

Current (amps)	Half-Width (cm. ⁻¹)			Separation of Maxima (cm. ⁻¹)	
	Entire	Component A	Component B	Component A	Component B
0.5	0.453	0.133	0.149	-----	-----
0.6	0.465	0.145	0.174	-----	-----
0.7	0.496	0.177	0.206	-----	0.067
0.8	0.525	0.199	0.236	0.077	0.099
0.9	0.561	0.250	0.273	0.099	0.112
1.0	0.605	0.276	0.329	0.114	0.125
1.1	0.798	-----	-----	0.159	0.177

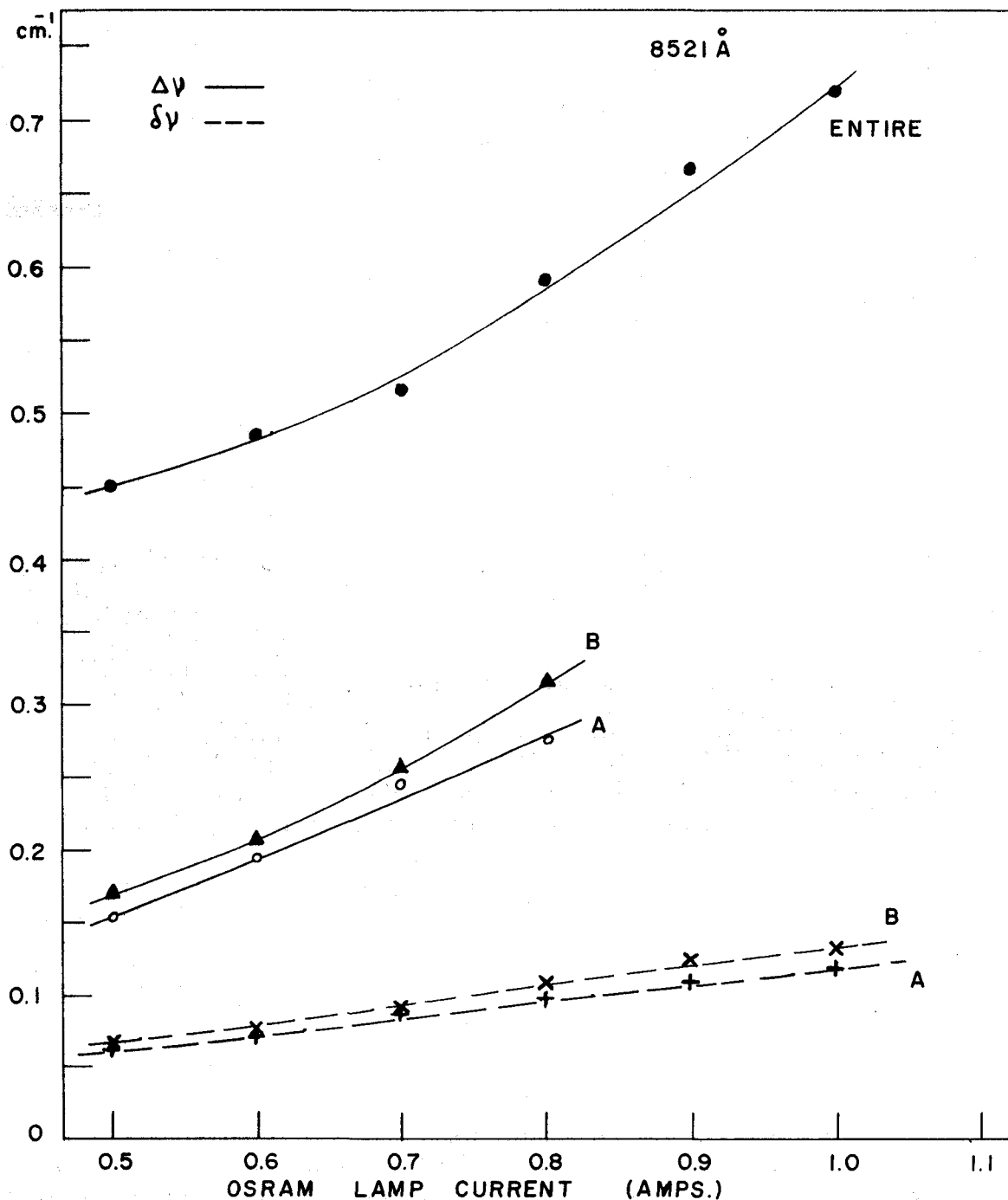


Fig. (12) Half-Widths, $\Delta\nu$ and Separations of the Self-Reversal Maxima, $\delta\nu$, in the Cesium 8521 Å components emitted by the Osram lamp. The curve marked Entire describes the shape formed by the merging A and B components.

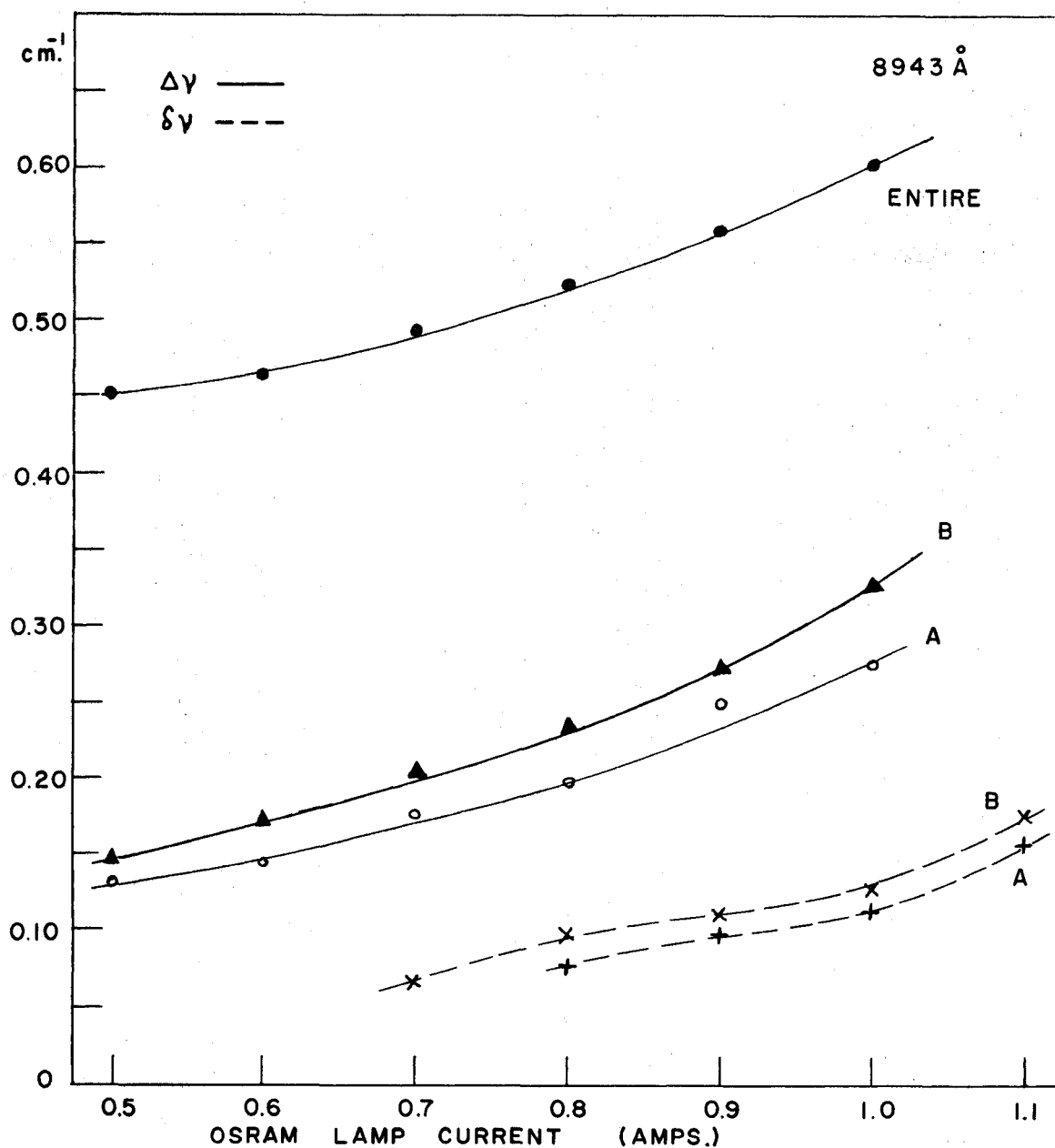


Fig. (13) Half-Widths, $\Delta\nu$, and Separations of the Self-Reversal Maxima, $\delta\nu$, in the Cesium 8943 Å components emitted by the Osram lamp. The curve marked Entire describes the shape formed by the merging A and B components.

longer be distinguished. The 8943 Å line showed similar behaviour as the lamp current was increased.

The 8943 Å and 8521 Å lines emitted by the Osram lamp were more self-reversed than the corresponding lines produced by the rf. lamps. For the 8943 Å line, the distance between the self-reversal peaks varied from 0.077 cm.⁻¹ at 0.8 amps and 0.067 cm.⁻¹ at 0.07 amps for the A and B components respectively, to 0.159 cm.⁻¹ and 0.177 cm.⁻¹ at 1.1 amps. The values for the 8521 Å line were slightly larger.

The half-widths of the h.f.s. components of both the 8521 Å and 8943 Å lines emitted by the rf. lamp are listed in Tables (8) and (9) and are plotted in Figs. (14) and (15) as functions of the lamp temperature. The hyperfine structure arises from the h.f.s. splitting of the $^2S_{1/2}$ ground state; the splitting in the 2P states is much smaller and was only partly resolved. The separations of the self-reversal maxima are also plotted in Figs. (14) and (15).

The half-width of the A component of the 8521 Å line varied from 0.052 cm.⁻¹ at 80 °C to 0.185 cm.⁻¹ at 160 °C while the half-width of the B component of the 8521 Å line ranged from 0.051 cm.⁻¹ at 80 °C to 0.204 cm.⁻¹ at 160 °C.

Table (8)

Half-Widths and Separations of the Self-Reversal Maxima
in the Cesium 8521 $\overset{\circ}{\text{A}}$ Component emitted
by the Radiofrequency Lamp

Temperature ($^{\circ}\text{C}$)	Half-Widths Component A	(cm^{-1}) Component B	Separation of Maxima (cm^{-1}) Component A	Component B
80	0.052	0.051	-----	-----
90	0.053	0.053	-----	-----
100	0.055	0.055	0.013	0.019
110	0.061	0.062	0.024	0.026
120	0.065	0.070	0.029	0.030
130	0.072	0.074	0.038	0.040
140	0.094	0.104	0.052	0.058
150	0.126	0.147	0.069	0.080
160	0.185	0.204	0.072	0.091

Table (9)

Half-Widths and Separations of the Self-Reversal Maxima

In the Cesium 8943 Å component emitted

by the Radiofrequency Lamp

Temperature (°C)	Half - Widths (cm. ⁻¹)		Separation of Maxima (cm. ⁻¹)			
	Components A	Components B	Components A	Components B	Components A	Components B
80	0.064	0.071	0.034	-----	0.034	-----
90	0.062	0.067	0.036	-----	0.037	-----
100	0.060	0.066	0.035	-----	0.037	-----
110	0.075	0.075	0.036	-----	0.034	-----
120	0.077	0.079	0.035	-----	0.029	-----
130	0.079	0.086	0.039	-----	0.030	-----
140	0.083	0.094	0.040	-----	0.033	0.064
150	0.111	0.069	0.044	0.072	0.036	0.077
160	0.155	0.172	0.054	0.095	0.050	0.104

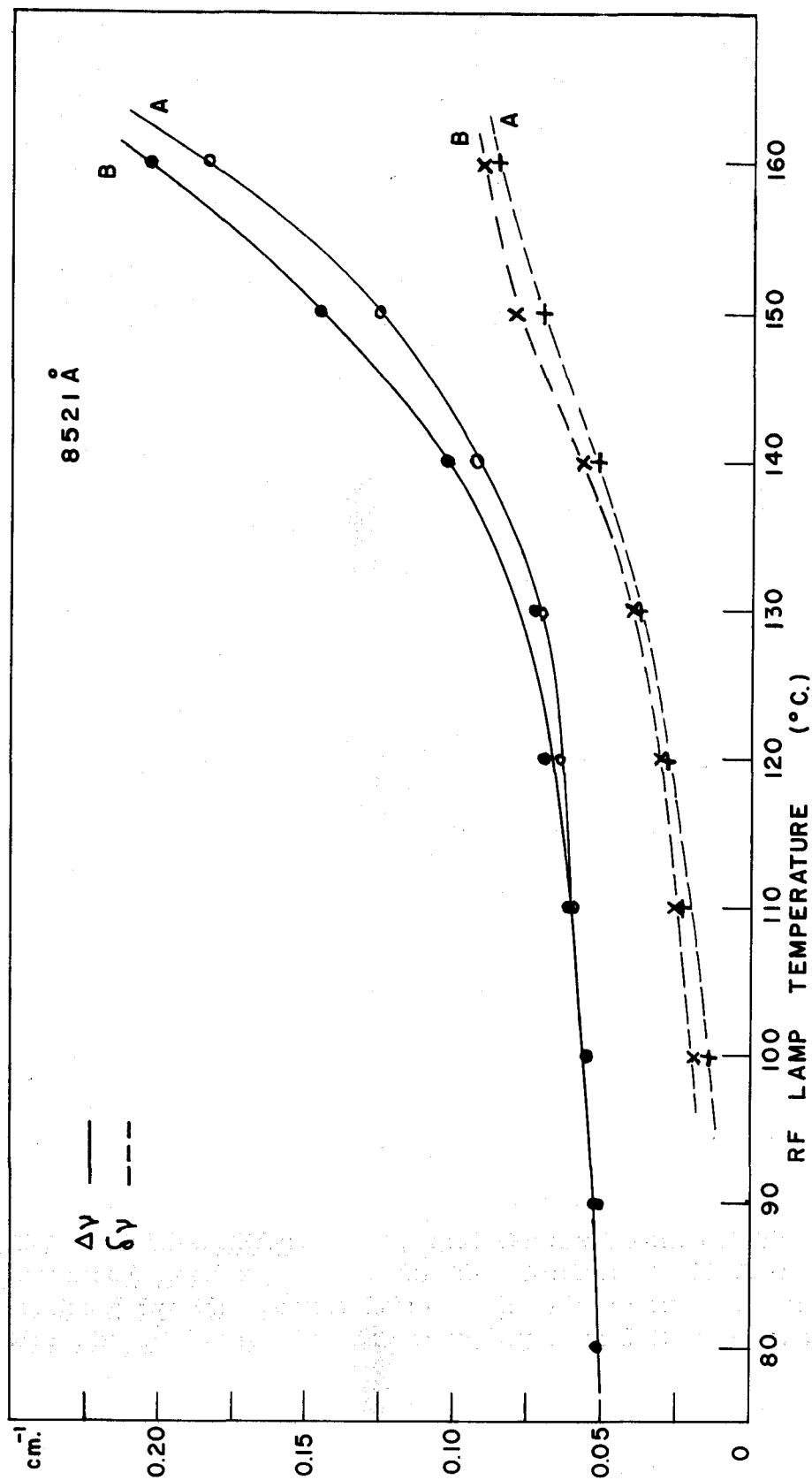


Fig. (14) Half-widths, $\Delta\nu$, and Separations of the Self-Reversal Maxima, $\delta\nu$, in the Cesium 8521 Å components emitted by the rf. lamp.

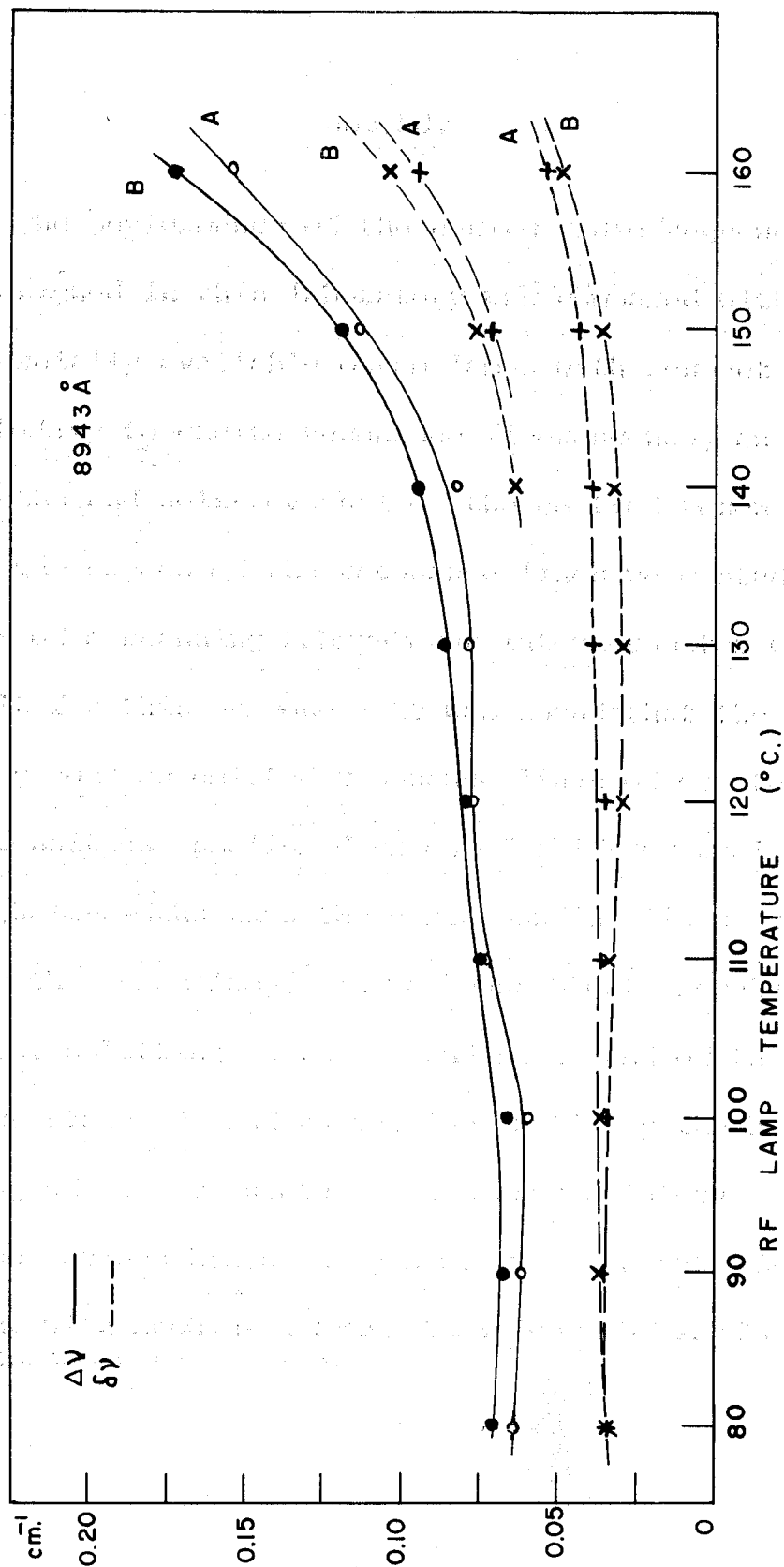


Fig. (15) Half-Widths, $\Delta\gamma$, and Separations of the Self-Reversal Maxima, $\delta\gamma$, in the Cesium 8943 Å components emitted by the rf. lamp. Short curves show the separation of peaks 1 and 3.

The peak separations for both the A and B components of the $8521 \text{ \AA}$ begin at 100°C in both cases, and range upwards from 0.013 cm^{-1} and 0.019 cm^{-1} at 100°C to 0.072 cm^{-1} and 0.091 cm^{-1} at 160°C , for A and B respectively. The corresponding half-widths for the A and B components of the $8943 \text{ \AA}$ line range from 0.064 cm^{-1} and 0.071 cm^{-1} at 80°C , to 0.155 cm^{-1} and 0.172 cm^{-1} , respectively, at 160°C . The peak separations within the A and B components of the $8943 \text{ \AA}$ resonance line rose from values of 0.034 cm^{-1} and 0.034 cm^{-1} , respectively, at 80°C , to 0.054 cm^{-1} and 0.050 cm^{-1} at 160°C . Above 140°C for the A component or 150°C for the B component, a second dip appeared in the line profile, which was due to true self-reversal.

(C) Hyperfine Structure

The hyperfine structure due to the ground state splitting was easily resolved in both the Osram and rf. lamps. The value obtained for both the $8521 \text{ \AA}$ and the $8943 \text{ \AA}$ line of the Osram lamp was 0.300 cm^{-1} . The precise value obtained by the method of radiofrequency spectroscopy is 0.30661 cm^{-1} (Millman and Kusch, 1940), which differs by 2.2% from the value obtained in this experiment. The values of the ground state splitting for the $8521 \text{ \AA}$ and the $8943 \text{ \AA}$

components emitted by the rf. lamp were 0.303 cm^{-1} and 0.307 cm^{-1} , which differed by 1.17% and 0.46% respectively from that of Millman and Kusch.

The hyperfine structure arising from the splitting in the P states was poorly resolved in the lines produced by the Osram lamp. However, the rf. lamp yielded values of 0.013 cm^{-1} and 0.019 cm^{-1} for the splitting in the A and B components, respectively, of the 8521 Å line. The total hyperfine structure separation for the $6^2P_{3/2}$, as measured by Jackson (1934) is 0.018 cm^{-1} . However, the energy separation between the transitions $F=5 \rightarrow F=4$ and $F=3 \rightarrow F=4$ is 0.0135 cm^{-1} , while between $F=4 \rightarrow F=3$ and $F=2 \rightarrow F=3$, the value is 0.0105 cm^{-1} (Kopferman and Kruger, 1936). Therefore it may be seen that the splitting in the $6^2P_{3/2}$ level was only partially resolved. In the 8943 Å line, the total h.f.s. for the $2P_{1/2}$ level was measured as 0.034 cm^{-1} in both the A and B components. These values agree within 8% with the value of 0.037 cm^{-1} found by Granath and Stranathan (1935).

(D) Self-Reversal

The ratios, $\frac{I_{\text{max}}}{I_{\gamma_0}}$, of the heights of the self-reversal peaks to the line centre, are plotted against the

operating parameters of both the Osram and rf. lamps in Figs. (16) and (17) .

Self-reversal is much stronger in the Osram lamp than in the rf. lamp. This is probably due to the fact that, in the volume discharge, most of the emitting atoms are concentrated about the axis of the discharge which is surrounded by slightly cooler vapour capable of absorbing the emitted radiation. In the radiofrequency lamp, on the other hand, a skin discharge is established near the wall of the lamp so that, viewed from the top, the wall of the lamp seems to glow brightly while the central part is dark. At higher temperatures, and thus higher vapour pressures, this effect is even more noticeable.

Atkinson (1964) suggested that light emitted in the excited layer near the back wall of the lamp is readily absorbed as it passes through the central, unexcited volume. Also, absorption may take place near the walls because of the presence of cooler vapour immediately adjacent to the walls, as the discharge tube was not shielded from air currents in the room, and also because of a higher concentration of atoms in an unexcited state, having previously lost their energy by collisions with the inner wall of the lamp. This was demonstrated by Atkinson when

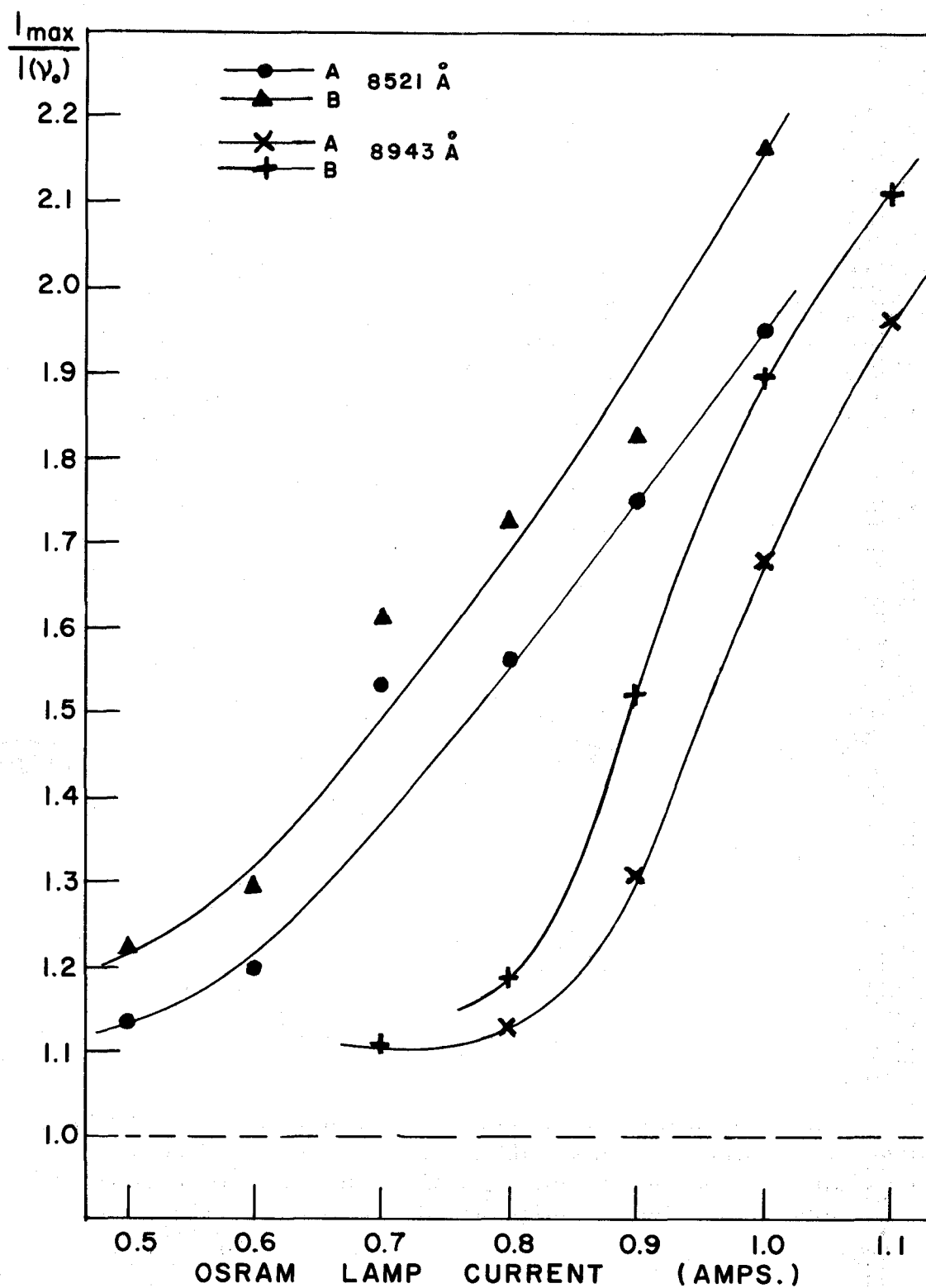


Fig. (16) Ratios of Intensities of Self-Reversal Peaks to Central Minima of the 8521 Å and 8943 Å components emitted by the Osram lamp.

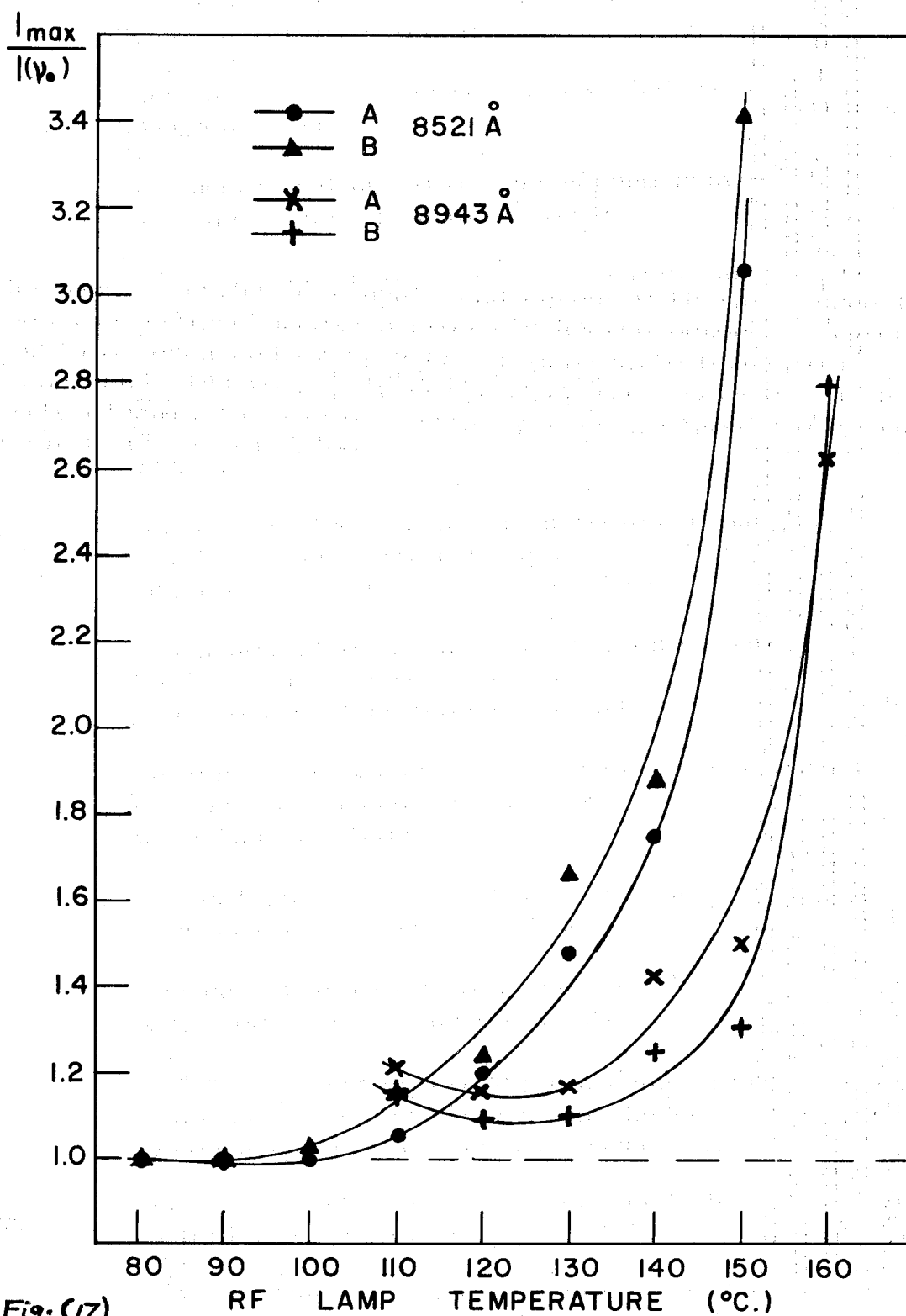


Fig. (17)
 Ratios of Intensities of Self-Reversal Peaks to Central Minima of the 8521 Å and 8943 Å components emitted by the rf. lamp.

he treated emission from different sections of the radio-frequency discharge tube.

(E) The Broadening of the Cesium Resonance Lines

The theory of self-absorption, as described in Chapter II, states that the square of the separation of the self-reversal peaks should vary either linearly or logarithmically with the absorption parameter p , provided that the half-width of the incident line is constant with pressure.

The appropriate curves were plotted for the A and B components of each cesium resonance line excited with both the Osram and rf. lamps. They appear in Figs. (18), (19), (20), and (21). Each curve demonstrated a linear rather than a logarithmic variation, indicating that the resonance broadening was more important than Doppler broadening. However, it is difficult to interpret the points at the upper limits of the operating conditions, as the stipulation that the half-width of the incident line is constant with pressure no longer holds in this region. Since the density of argon in the lamps remained the same, Stark broadening and collision broadening by argon ions would be nearly a constant.

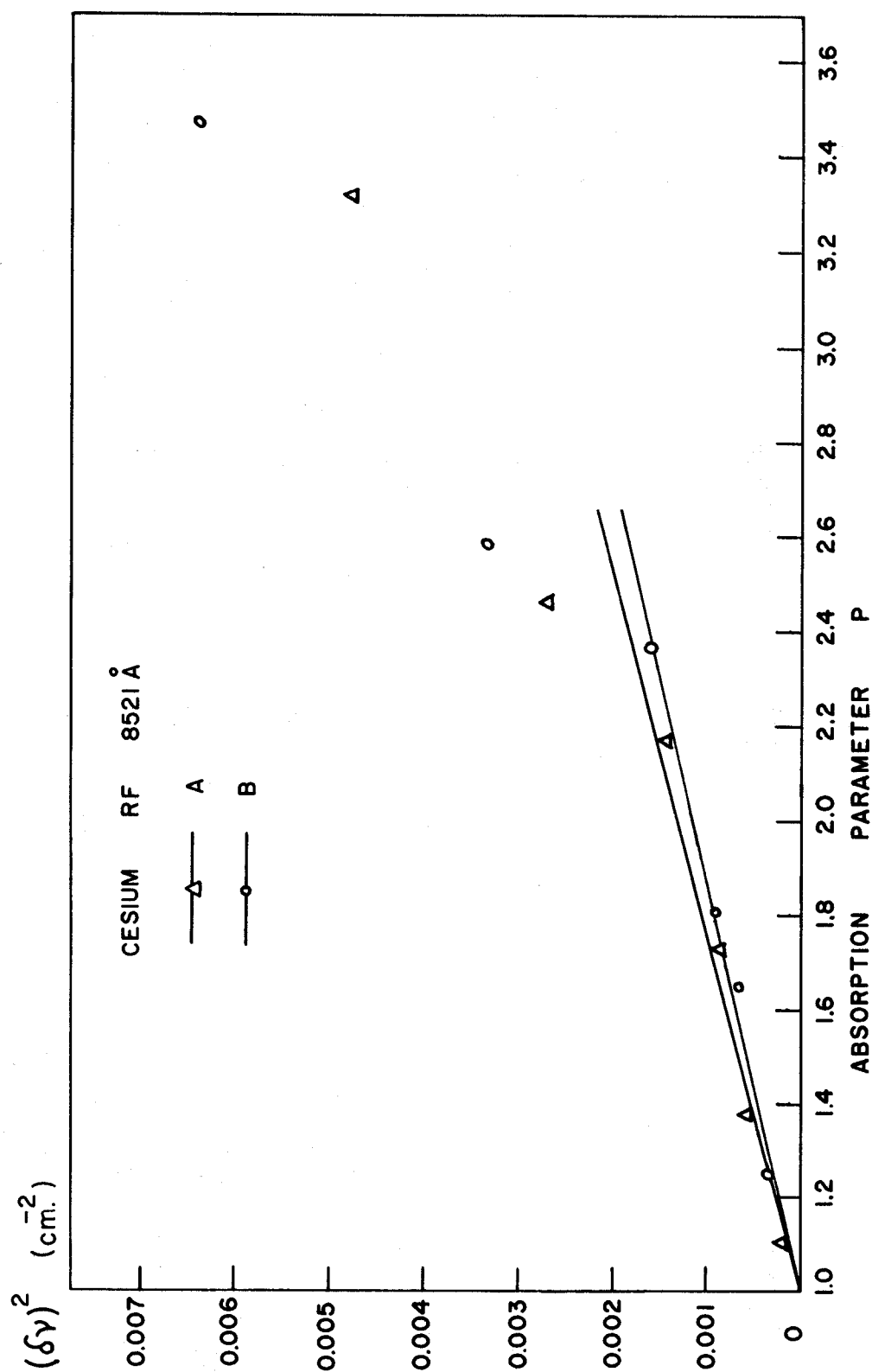


Fig. (18) Plot of the Square of Self-Reversal Peak Separations vs. Absorption Parameter in the Cesium 8521 Å components emitted by the rf. lamp.

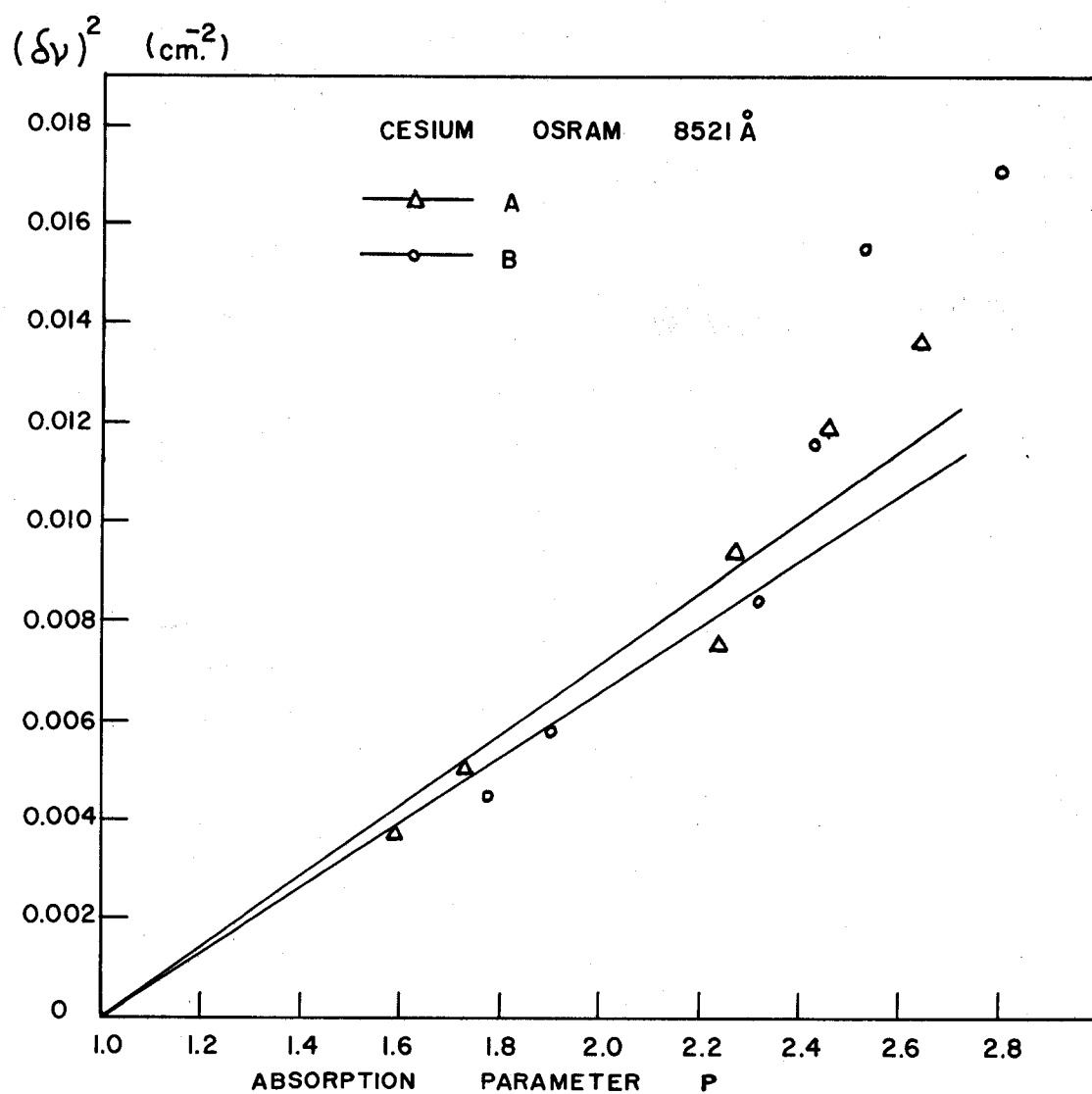


Fig. (19) Plot of the Square of Self-Reversal Peak Separations vs. Absorption Parameter in the Cesium 8521 Å components emitted by the Osram lamp.

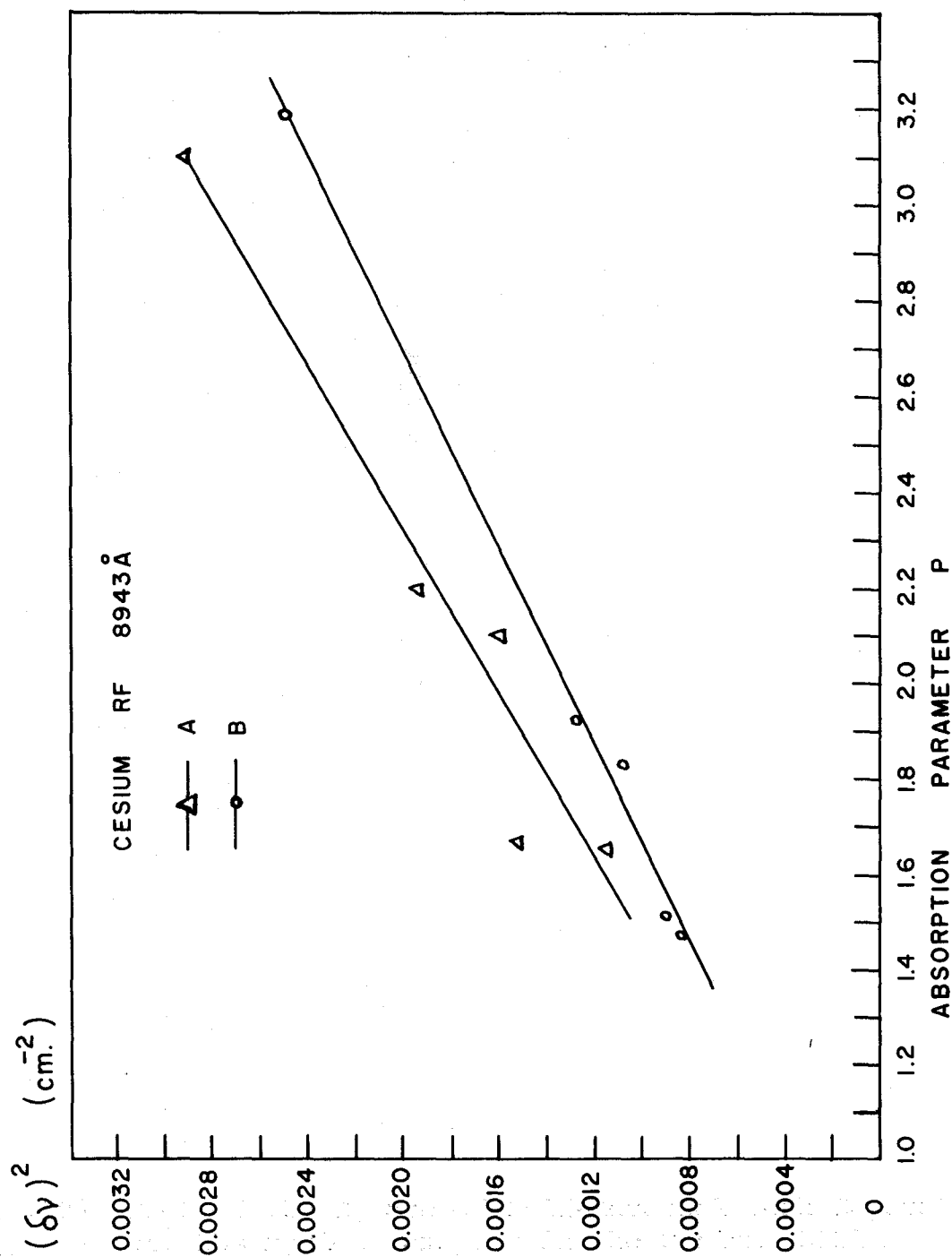


Fig. (20) Plot of the Square of Self-Reversal Peak Separations vs. Absorption Parameter in the Cesium 8943 Å components emitted by the rf. lamp.

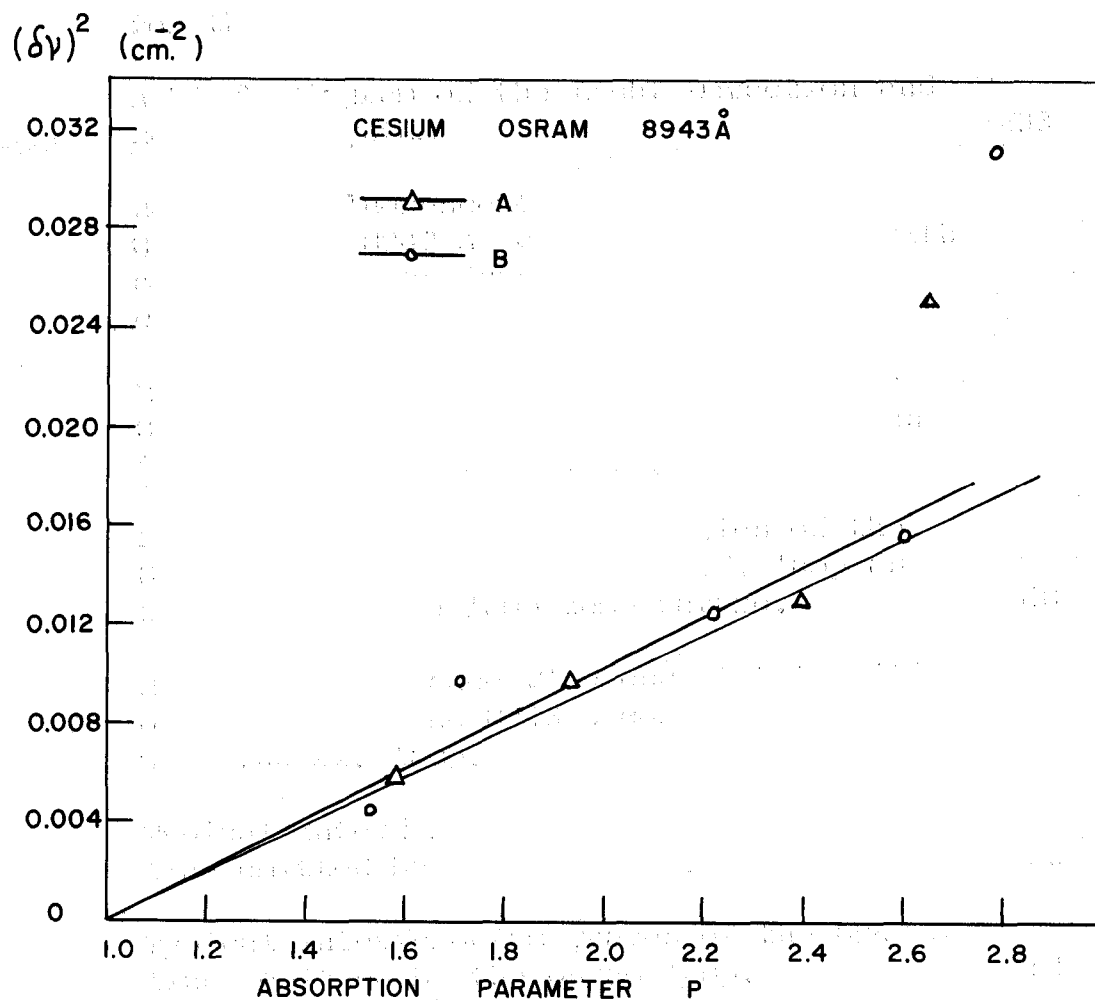


Fig. (21) Plot of the Square of Self-Reversal Peak Separations vs. Absorption Parameter in the Cesium 8943 Å components emitted by the Osram lamp.

CONCLUSIONS

A determination of the relative usefulness of Osram and rf. cesium lamps was carried out using a scanning interferometer built in this laboratory. Measurements were made of the half-widths and the degrees of self-reversal of the resonance lines. The lamps were also rated as to their ability to excite resonance fluorescence in cesium vapour.

It was found, for both the $8521\text{ \AA}$ and $8943\text{ \AA}$ lines, that the rf. lamps containing the lowest pressure of argon were able to excite resonance fluorescence of the highest intensity. With an argon pressure of 0.5 torr, the maximum resonance fluorescent intensities were about 10 times larger than those produced by the Osram lamp, while at one torr of argon, the ratio was only about 8:1. With both Osram and rf. lamps it was possible to observe the h.f.s. splitting of the ground state. Although the total hyperfine splitting of the $^2P_{1/2}$ states could not be resolved in the lines emitted by the Osram lamp, it was readily measured for the sharper lines produced by the rf. lamps.

The radiofrequency cesium spectral lamps are by far superior to commercially-produced spectral lamps for the

purpose of exciting resonance fluorescence in cesium vapour.

The Fabry-Perot scanning interferometer built in this laboratory has proven itself to be a useful instrument in studying the shapes of spectral lines. It is hoped that even better resolution will be achieved by the use of etalons of a higher reflectance.

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White, H.E., 1934, Introduction to Atomic Spectra,
McGraw-Hill, Appendix Table 3.

VITA AUCTORIS

I was born in Windsor, Ontario, on November 19, 1941. After graduating from Riverside High School in 1960 with a Senior Matriculation, I enrolled at Assumption University of Windsor, which in 1963 became the University of Windsor. In 1964 I graduated with an honours Bachelor of Science degree in Physics and Chemistry from the University of Windsor. After teaching senior high school physics for one year, I returned to continue my studies in physics at the University of Windsor. I was awarded a Province of Ontario Fellowship for the year 1966-67.