LINE PROFILES IN A NEON GLOW PLASMA

by

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Abstract

A new experimental technique has been developed for the determination of absorption line profiles in steady-state plasmas. The method involves observing the total transmitted line intensity of one component of the longitudinal Zeeman pattern from a background source. The frequency shift of this line is determined from the known magnetic field and the Landé g-factors involved. The light from the background source is amplitude modulated by a chopping wheel, and the intensity of the transmitted light is measured with a phase-sensitive detector.

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CHAPTER I

Introduction

Historically, spectroscopic methods have been used extensively for the study of plasmas. This broad application has arisen because plasmas naturally are light emitters, the wavelength of light is short so that spatial resolution is good, and data may be obtained with little or no perturbation of the plasma. In astrophysical plasmas, the only tool available is spectroscopy since the sources are far removed. Usually the spectroscopist looks at either the line intensities at various wavelengths or the individual line shapes. In the former case, if the transition probabilities are known, relative abundances of excited atoms and ions may be obtained and estimates of temperature and degree of ionization made. In the latter case the shape of the line depends on many factors -- for example, the transition probability, the gas temperature, the pressure, the density of charged particles. If the line shape could be precisely determined and the contributions of the various factors assessed, many physical properties of the plasma could be determined.

The particular interest in determining the line shapes for a Neon glow plasma, as reported here, was generated by previous experiments in this laboratory (Robinson[16] and Irwin[11]) which determined oscillator strengths in Neon by absorption methods. The analysis of these experiments assumed a

Doppler-broadened line, and it was deemed desirable to check this assumption experimentally and to determine the magnitude of the departure from Doppler shape. The object of the experiment reported here is to check the feasibility of determining this departure experimentally with a novel technique.

Also, if a good technique could be developed to determine line shapes, then it could be used to study the effects of pressure broadening of spectral lines at relatively low pressures. This is an area where few results have been published, because of the difficulty in determining by present techniques the shape of such narrow lines accurately.

We use an intensity-modulated, frequency-modulated background source, and a phase-sensitive detector to measure the total light intensity transmitted through an absorption tube. From a measure of this line intensity as a function of frequency shift (given by the Zeeman splitting), we determine the percent transmission as a function of frequency. This then allows us to infer (from a computer approximation) the shapes of the absorption lines.

In the experiment reported here, the line width of the background source and absorber were comparable. It is conceivable that under such conditions an appropriate involution of the curve would give the shape of both the emitter and absorber. Some attempt has been made at this and it is shown that the method is indeed feasible. It is obvious, though, that a better result would obtain if the line width of the emitter were significantly less than that of the absorber. It was not within the scope of the present work to pursue this possibility.

CHAPTER II

Theory

(a) Absorption of Radiation

We consider a parallel beam of light of intensity I_ν in the frequency range ν to $\nu+d\nu$ incident on a medium composed of atoms capable of absorbing the light. We suppose there are N_1 atoms per cc. in the lower state of which δN_1 are capable of absorbing in the frequency range ν to $\nu+d\nu$, and N_2 atoms in an excited state of which δN_2 are capable of emitting in this frequency range.

As the beam traverses a layer of atoms of thickness dx, then intensity at frequency ν will change by:

$$-d(I_\nu\delta\nu) = \delta N_1 dx\ h\nu\ B_{12}\frac{I_\nu}{4\pi} - \delta N_2\ dx\ h\nu\ B_{21}\frac{I_\nu}{4\pi} - \delta N_2\ dx\ h\nu\frac{A_{21}}{4\pi}$$

If we have abailable a means for distinguishing between the beam radiation and the spontaneous emission from the absorbing medium, we can neglect the last term in the equation, giving us:

$$-d(I_\nu\delta\nu) = N_1 dxh\ B_{12}\frac{I_\nu}{4\pi} - \delta N_2 dxh\nu B_{21}\frac{I_\nu}{4\pi}$$

The B's are the Einstein coefficients, such that $B_{12}I_\nu$ is the probability (per atom) per second that the atom in state 1 will absorb a quantum $h\nu$ and end up in state 2 when exposed to radiation of intensity I_ν in the frequency range ν to

$\nu + d\nu$. $I\nu/4\pi$ is the intensity of equivalent isotropic radiation for which the B's are defined.

Hence we have:

$$-\frac{1}{I_\nu}\frac{dI_\nu}{dx}\,\delta\nu = \frac{h\nu}{4\pi}\,(B_{12}\,\delta N_1 - B_{21}\,\delta N_2)$$

Comparing this to the definition of the absorption coefficient at the frequency ν :

$$\frac{dI\nu}{dx} = -I\nu\; k_\nu ,$$

we have the connecting relation:

$$k_\nu\,\delta\nu = \frac{h\nu}{4\pi}\,(B_{12}\,\delta N_1 - B_{21}\,\delta N_2).$$

If we consider the limit as $\delta\nu \rightarrow 0$, and integrate, we have:

$$\int_{\text{line}} k_\nu\, d\nu = \int_{\text{line}} \frac{h\nu}{4\pi}\,(B_{12}\, dN_1 - B_{21}\, dN_2)$$

$$= \frac{h\nu_o}{4\pi}\,(B_{12}\, N_1 - B_{21}\, N_2),$$

where N_1 is the number density of the lower state and N_2 the upper.

The Einstein coefficients are related [4] by:

$$\frac{A_{21}}{B_{12}} = \frac{2h\nu^3}{c^2} \quad \frac{g_1}{g_2}$$

$$\frac{B_{21}}{B_{12}} = \frac{g_1}{g_2},$$

where the g's represent the degeneracies of the states 1 and 2.

It is customary to define the lifetime for the transition from state 2 to state 1 as:

$$\tau = \frac{1}{A_{21}}$$

Using these relations we have:

$$\int_{line} k_\nu \, d\nu = \frac{\lambda_o^2}{8\pi\tau} \frac{g_2}{g_1} N_1 \left(1 - \frac{N_2}{N_1} \frac{g_1}{g_2}\right)$$

This relation is true for any absorption line shape, and hence is independent of the broadening mechanism.

In terms of the oscillator strength for the transition we have

$$\int_{line} k_\nu \, d\nu = N_1 f_{12} \frac{\pi e^2}{mc} \left(1 - \frac{N_2}{N_1} \frac{g_1}{g_2}\right),$$

In most cases the population of the upper level is much smaller than that of the lower level, and in this approximation:

$$\int_{\text{line}} k_{\nu}\, d\nu = 0.024\, f_{12}\, N_1$$

(b) <u>Absorption of Line Radiation</u>

From section (a) we have:

$$\frac{dI_{\nu}}{dx} = -I_{\nu}\, k_{\nu},$$

where k_{ν} is the absorption coefficient at frequency ν.

Solving this gives:

$$I_{\nu}(\ell) = I_{\nu}(o)\; e^{-k_{\nu}\ell},$$

where $I_{\nu}(\ell)$ is the intensity in the frequency interval ν to $\nu + d\nu$ after traversing a path of length ℓ cm., and I_{ν} (o) is the incident intensity in the same frequency range.

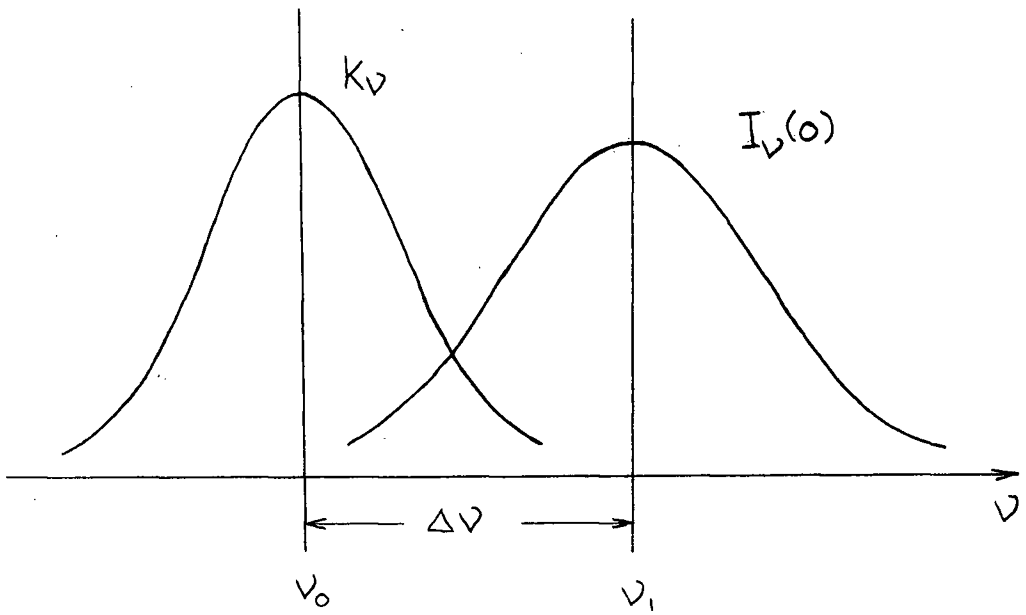
If the detecting instrument gives a reading proportional to the total (integrated) line intensity, as in a monochromater-photomultiplier arrangement say, then the recorded response is proportional to:

$$I(\ell) = \int_{\text{line}} I_{\nu}(o)\; e^{-k_{\nu}\ell}\, d\nu.$$

The percent transmission is then given by:

$$= \frac{\int_{\text{line}} I_{\nu}(o) e^{-k_{\nu}\ell} d\nu}{\int_{\text{line}} I_{\nu}(o)\; d\nu}.$$

Note that $I_\nu(o)$ and k_ν are functions of the frequency ν, and that $I_\nu(o)$ and k_ν may be of different shape and need not be centered on the same frequency:



In this experiment the incident light is derived from one component of the longitudinal Zeeman pattern, and hence the spacing $\Delta\nu$ is determined by the Zeeman splitting.

If we consider the frequency measured from the centre of the lines, we have:

$$k_\nu = k\ (w) \quad \text{and}$$
$$I_\nu(o) = I\ (w - \Delta\nu),$$

where $w = \nu - \nu_o$. This gives us for the transmission:

$$T\ (\Delta\nu) = \frac{\int_{\text{line}} I\ (w - \Delta\nu)\ e^{-k(w)\ell}\ dw}{\int_{\text{line}} I\ (w - \Delta\nu)\ dw},$$

which is a convolution integral of complicated functions.

(c) Broadening of Spectral Lines

(i) Natural Line Broadening

An atom emits radiation when an atomic electron makes a transition from an upper energy state to a lower state. From Quantum Theory we know that the atomic states with finite lifetimes do not have a precisely defined energy, but encompass a range of energies:

$$\Delta E = \frac{\hbar}{\Delta t},$$

where Δt is the lifetime of the state.

A quantum mechanical treatment of the process of emission of radiation shows (10) the intensity distribtuion within a line to be:

$$I_\nu = \frac{(\gamma/2\pi)}{\left[\nu - \nu_{21}\right]^2 + \left[\frac{\gamma}{2}\right]^2},$$

where ν_{21} = the Bohr frequency $\frac{E_2 - E_1}{h}$ for the transition between the states 1 and 2,

and $$\gamma = \gamma_1 + \gamma_2$$

$$= \frac{\Delta E_1}{h} + \frac{\Delta E_2}{h}$$

We see that $\gamma_1 = \frac{1}{2\pi\Delta t_1}$ from the uncertainty relation above.

If the atom is in state 1, then $1/\Delta t_1$ is (approximately) the number of spontaneous transitions which can occur per second.

If k is a lower state capable of combination with state 1, then the number of transitions $1 \longrightarrow k$ is:

$$\frac{8\pi^2 e^2}{mc^3} \nu^2_{1k} \quad f_{1k}$$

where ν_{1k} = Bohr frequency

f_{1k} = oscillator strength for the transition.

$$\therefore \quad \frac{1}{\Delta t_1} = \frac{8\pi^2 e^2}{mc^3} \sum_k \nu^2_{1k} \quad f_{1k} \quad ,$$

and so

$$\Delta E_1 = \hbar \frac{8\pi^2 e^2}{mc^3} \sum_k \nu^2_{1k} \quad f_{1k} \quad .$$

Hence if we consider the broadening of both levels 1 and 2, we have:

$$\gamma = \frac{4\pi e^2}{mc^3} \left\{ \sum_k \nu^2_{1k} \quad f_{1k} + \sum_\ell \nu^2_{2\ell} \, f_{2\ell} \right\} .$$

In all cases considered here the natural half width is much smaller than the width associated with any other broadening mechanism, and hence natural broadening can be considered as a negligible effect.

(ii) Doppler Broadening

If we assume that every atom at rest emits monochromatic radiation of frequency ν_0, we find that the light from any practical source is broadened because of the thermal motion of the emitters in the source. Similarly, the absorption line is broadened because of the thermal motion of the absorbers.

If we consider a beam of parallel light travelling in the positive x direction, atoms moving with a speed v_x in this direction will absorb light from the beam of frequency $\nu = \nu_o (1 + {}^{Vx}/c)$. If we assume thermal equilibrium, we know that the number of particles dn with velocity component in the range Vx to Vx + dx is:

$$dn = n\sqrt{\frac{m}{2\pi kT}}\; e^{-\left(\frac{m}{2kT}\right)V_x^2}\, dV_x$$

where m is the atomic weight of the absorbers, and T is the absolute temperature.

Since the velocity component is related to the frequency absorbed by:

$$Vx = \frac{c}{\nu_o}\left(\nu - \nu_o\right) ,$$

we can see that the absorption coefficient must be of the form:

$$k_\nu = k_o \; e^{-\left(\frac{m}{2kt}\right)\frac{c^2}{\nu_o^2}(\nu - \nu_o)^2} \quad cm^{-1} ,$$

which is a Gaussian function of $(\nu - \nu_o)$.

The half-width of the Doppler-broadened lines is given by:

$$\Delta \nu_d = 2\,(\ln 2)^{\frac{1}{2}} \left(\frac{2kT}{mc^2}\right)^{\frac{1}{2}} \nu_o \quad \sec^{-1}$$

This gives for the half width:

$$\frac{\Delta \nu_d}{\nu_o} = 0.71 \times 10^{-6} \sqrt{\frac{T}{M}}$$

$$= \frac{\Delta \lambda_d}{\lambda_o} \quad ,$$

where $\Delta \lambda_d$ is the half width in terms of wavelength, for a "line" of wavelength λ_o.

For the plasmas used in this experiment the main broadening mechanism is the Doppler effect. If we assume that the absorption coefficient is completely determined by the Doppler profile, we have:

$$\int_{line} k_\nu \; d\nu = k_o \int e^{-\left\{\frac{2\sqrt{\ln 2}\,(\nu - \nu_o)}{\Delta \nu_d}\right\}^2} d\nu$$

$$= k_o \sqrt{\frac{\pi}{\ln 2}} \; \frac{\Delta \nu_d}{2}$$

But from section (a) we have:

$$\int_{line} k_\nu \; d\nu = 0.024 \; f_{12} \, N_1 \quad ,$$

independent of any broadening mechanism.

$$\therefore \quad k_o = 0.0225 \frac{f_{12} N_1}{\Delta \nu_d} \quad cm^{-1}$$

$$= 0.75 \times 10^{-12} \frac{f_{12} N_1}{\Delta \lambda_d} \lambda_o^2 \quad cm^{-1}$$

(iii) Pressure Broadening

It is found that the spectral lines emitted by a gas at high pressure are broader than (and sometimes shifted with respect to) those lines emitted by the same gas at lower pressure. This broadening occurs because the emitting atom is perturbed by its neighbours. Because this problem is a very difficult one theoretically, the theories of pressure broadening have developed at each extreme of approximation. These two extremes give rise to the impact (or interruption) broadening and statistical broadening theories. In the impact theory, the mean time between "collisions" is much greater than the duration of the collision, and only binary collisions are considered. This theory can be seen to have some validity in the case of a rarified gas, and for the plasmas studied in this experiment the impact theory could be expected to be a fairly good approximation. In the statistical theory, the emitting atom is considered to be in a constant state of perturbation, the atom and its neighbors forming a quasistatic aggregate (a pseudo-molecule). This theory is capable of giving a better approximation in the case of dense gases, or liquids.

Since the impact theory can be expected to provide a fairly good approximation in the case of the low density, weakly ionized plasmas used in this experiment, we will consider further this viewpoint, following the simple approach of Lorentz[10] :

If we consider an atom to emit an infinitely long wave-train in the absence of collisions, we may look upon the impacts with other particles as giving rise to interruptions of this wave-train, with the phase changing randomly during the collision. We assume that the collision time is much smaller than the mean flight time τ. The probability density of a flight time t is given by:

$$f(t) = \frac{1}{\tau} e^{-t/\tau}$$

During the time interval 0 to t, the wave is sinuscidal and so we have:

$$E(t) = E_0 e^{i\nu_0 t}$$

$$\therefore \quad E(\nu) = \frac{1}{2\pi} \int_0^t E_0 e^{i\nu_0 t} e^{-i\nu t'} dt'$$

$$= \frac{E_0}{2\pi} \frac{e^{i(\nu_0-\nu)t} - 1}{i(\nu_0-\nu)}$$

The intensity is given by:

$$I(\nu) = \overline{|E(\nu)|^2}$$

$$= \frac{E_0^2}{4\pi^2} \int_0^\infty \frac{\left| e^{i(\nu_0-\nu)t} - 1 \right|^2}{(\nu_0 - \nu)^2} \frac{e^{-t/\tau}}{\tau} \, dt$$

$$= \frac{E_0^2}{2\pi^2} \frac{1}{(\nu-\nu_0)^2 + (1/\tau)^2}$$

and hence the half width is given by:

$$\Delta\nu_p = \frac{2}{\tau} \qquad \sec^{-1}$$

The mean flight time τ can be found from the relevant cross section:

$$\tau = \frac{1}{\sqrt{2} \quad \pi \rho^2 \quad \bar{v} \quad n} \qquad \text{sec.,}$$

where ρ is the effective "radius" of the atom,

$\bar{v}$ is the average velocity,

n is the particle density.

$$\therefore \quad \tau = \sqrt{\pi mkT} \quad \frac{1}{4 \; P \; \sigma} \qquad \text{sec.,}$$

where P is the pressure in dynes/cm^2,

m is the atomic mass in grams,

$\sigma = \pi \rho^2$ is the collision cross-section.

$$\therefore \Delta\nu_p = 8 P \sigma \sqrt{\frac{1}{\pi m k T}} \quad \sec^{-1}$$

$$= \frac{5.12 \times 10^{11} \tilde{P} \sigma}{\sqrt{mT}} \quad \sec^{-1}$$

where $\tilde{P}$ is the pressure in mm Hg.

In terms of wavelength:

$$\Delta\lambda_p = 17.1 \times \frac{\tilde{P} \sigma \lambda_0^2}{\sqrt{mT}} \quad \text{cm}.$$

We should note that the "optical cross-section" σ can be significantly larger than the "kinetic cross-section" which appears in equations of diffusion etc.

More involved derivations(2) give rise to an expression:

$$I(\nu) = \frac{I_0}{\left(\frac{2\pi}{\alpha}\right)^2} \frac{1}{\left(\nu - \nu_0 + \frac{\beta}{2\pi}\right)^2 + \left(\frac{\alpha}{2\pi}\right)^2}$$

for the intensity distribution in a line which is broadened and shifted by collisions. The frequency shift ($\beta/2\pi$) is of the order of 1/10 to 1/2 of the half-width (α/π), depending on the line(5).

(iv) Stark Broadening

Since there are charged particles present in the glow dishcarge plasma we might expect some broadening effects due to the collisions of the emitting (or absorbing) atoms with charged perturbers. Since the current through the tubes is small (5ma and 2ma), and the pressure is low (10mm and 2mm), the charge density is also small and should not exceed 10^{11} particles per cubic centimeter[7]. To obtain an order of magnitude result for "Stark half-width" we can use the formula (8) for perturbation by electrons (since this will be the largest ionic effect):

$$\delta_c \approx \frac{9\, \hbar^2\, \alpha^2\, N}{16\, m^2\, \bar{u}} (0.923)$$

where $\alpha = 3$ for the Neon lines studied.

This gives

$$\delta_c \approx 2.85 \times 10^{-6}\ N\ \mathrm{sec}^{-1}$$

for an electron temperature of about 2ev.

This is a completely negligible effect for this experiment:

N	$\delta_c \lambda$
10^{11}	$.38 \times 10^{-5}$ Å
10^{12}	$.38 \times 10^{-4}$ Å
.	.
.	.
.	.
10^{17}	3.8Å

(v) Result Line Profile if more than one broading mechanism is present

If we consider a line to be broadened by different mechanisms -- Doppler, natural, pressure and Stark broadening -- we can, in a first approximation, consider each of the mechanisms to act independently. In this approximation we can consider each small element of the Lorentz profile to be Doppler broadened, or vice versa. This results in an expression for the absorption coefficient:

$$K_\nu = \frac{2K_0}{\pi(\Delta\nu_N + \Delta\nu_L)} \int_{-\infty}^{\infty} \frac{\exp -\left(\frac{2\delta}{\Delta\nu_d}\sqrt{\ln 2}\right)^2}{1 + \left[\frac{2(\nu - \nu_0 - \delta)}{\Delta\nu_N + \Delta\nu_L}\right]^2} \, d\delta$$

where the $\Delta\nu$'s are the half-widths associated with each of the mechanisms. This resultant expression is called a Voigt profile, and there has been extensive numerical work done on computing these profiles as a function of the parameter $a = \dfrac{\Delta\nu_N + \Delta\nu_L}{\Delta\nu_0}$.

This I will call the "Voigt a parameter."

(vi) Broadening due to Self-Absorption

For completeness sake, I should include self-absorption as a broadening mechanism. Although in some cases the study of absorbed lines can give useful and important information about the material located between the source and the detector, in this experiment self-absorption in the background source is an unwanted (because it is essentially unknown) broadening mechanism. It should be noted that all sources produce emission lines which are self-absorbed to a greater or lesser degree, and this can cause discrepancies in the measurement of the total intensity of spectral lines and their shapes.

The inherent difficulty due to self-absorption in this experiment lies in the fact that the transmission profile depends on the shape of the background emission line. This shape is determined by the mechanisms outlined previously, and also by self-absorption. Whereas the other causes are known with some accuracy, the fact we are viewing an inhomogendous plasma side-on makes the analysis of the effect of self-absorption very difficult to account.

For a homogeneous with "line of sight depth" ℓ, we find that the intensity profile is given by*:

$$I_{\nu} \propto 1 - e^{-k\ell}$$

* See Appendix

(d) Effects of the Magnetic Field

(i) Zeeman Effect in Neon

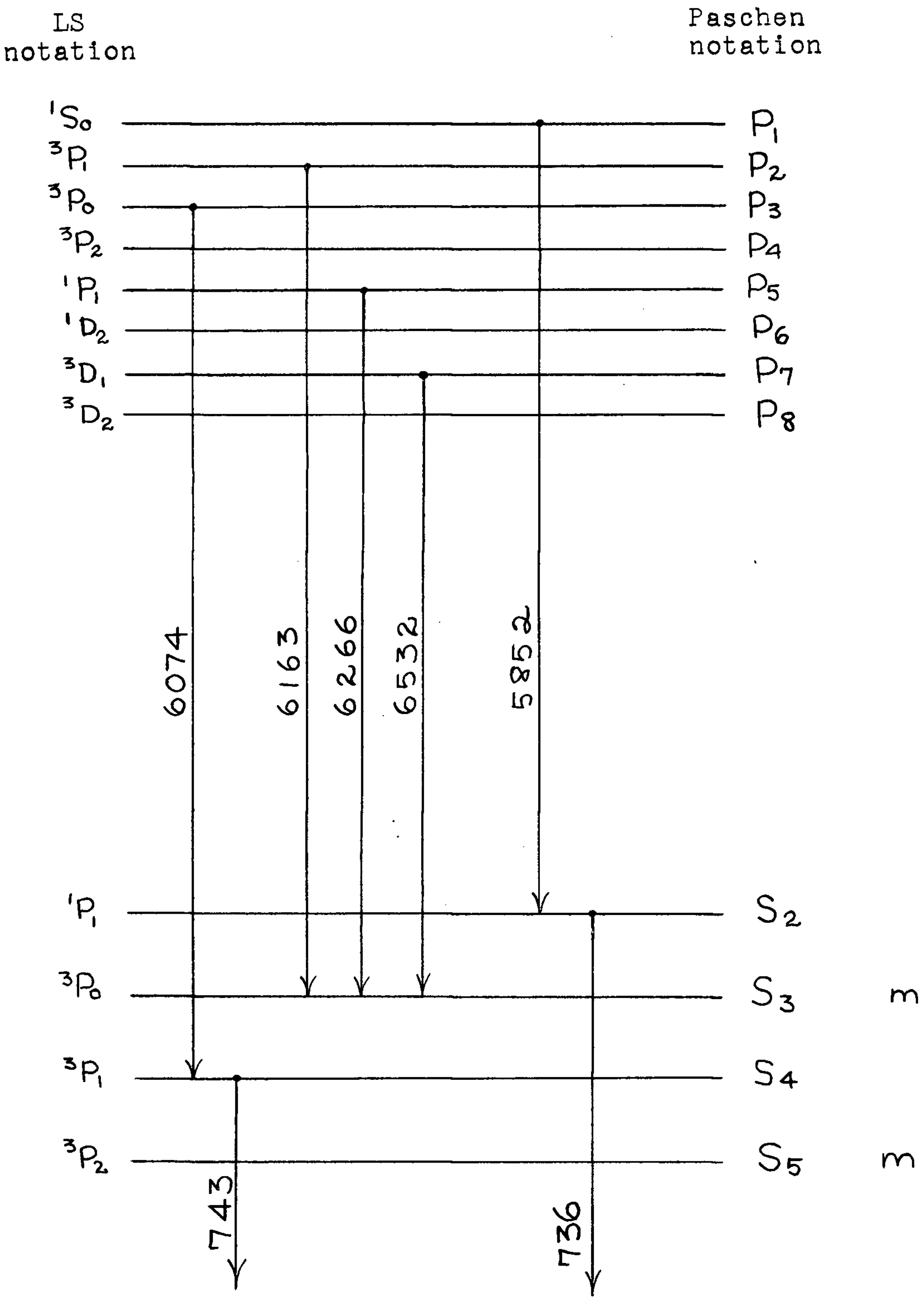
In this experiment the aim is to determine the absorption line profile from a measurement of the transmission as a function of the frequency shift. It has been found, however, that the shape of the background line has a marked effect on the transmission. To aid in simplifying the analysis, then, we have been led to studying those lines which exhibit the normal triplet pattern. Fortunately, the Zeeman effect in Neon has been studied carefully, and excellent data exist[1] to facilitate our search. Most of the 3P - 3S lines in the Neon spectrum exhibit a complex Zeeman structure, but there are a few which have the triplet pattern -- the 5852, 6074, 6163, 6266 and 6532 lines.

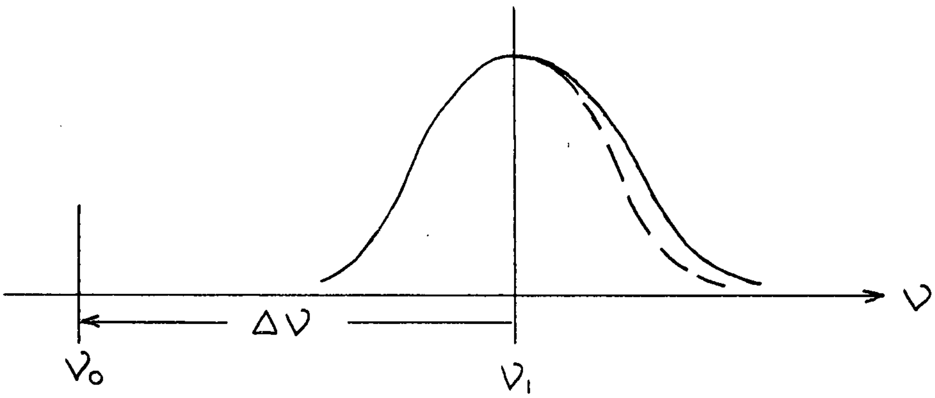
(ii) Accompanying Effects

The magnetic field, if it is not homogeneous across the emitting volume, will give rise to Zeeman components of slightly different frequency shifts from different parts of the source. This will result in a broader emission line, which is asymmetrical with respect to the peak:

see P. 22

Figure 1 -- Partial Term Diagram of Neon
Showing Zeeman Triplet Lines





This asymmetrical broadening will increase with field strength and hence the background line width will be greater when we are making measurements in the wings of the line.

The magnetic field will cause the charged particles to gryate around the field lines. Since the field lines are perpendicular to the tube this may drive the particles into the walls if the Larmour radius is greater than the tube radius. This will result in an increase in the tube resistance since we must apply a larger voltage to make up for these losses to the walls. It is found that for the fields used in this experiment that the electron Larmour radius is much less than the tube radius. This means that the electrons will be "contained" by the field, and will travel farther in the discharge before being lost. They will, then, be able to make more collisions and so increase the number of excited atoms.

CHAPTER III

Experiment

(a) Apparatus

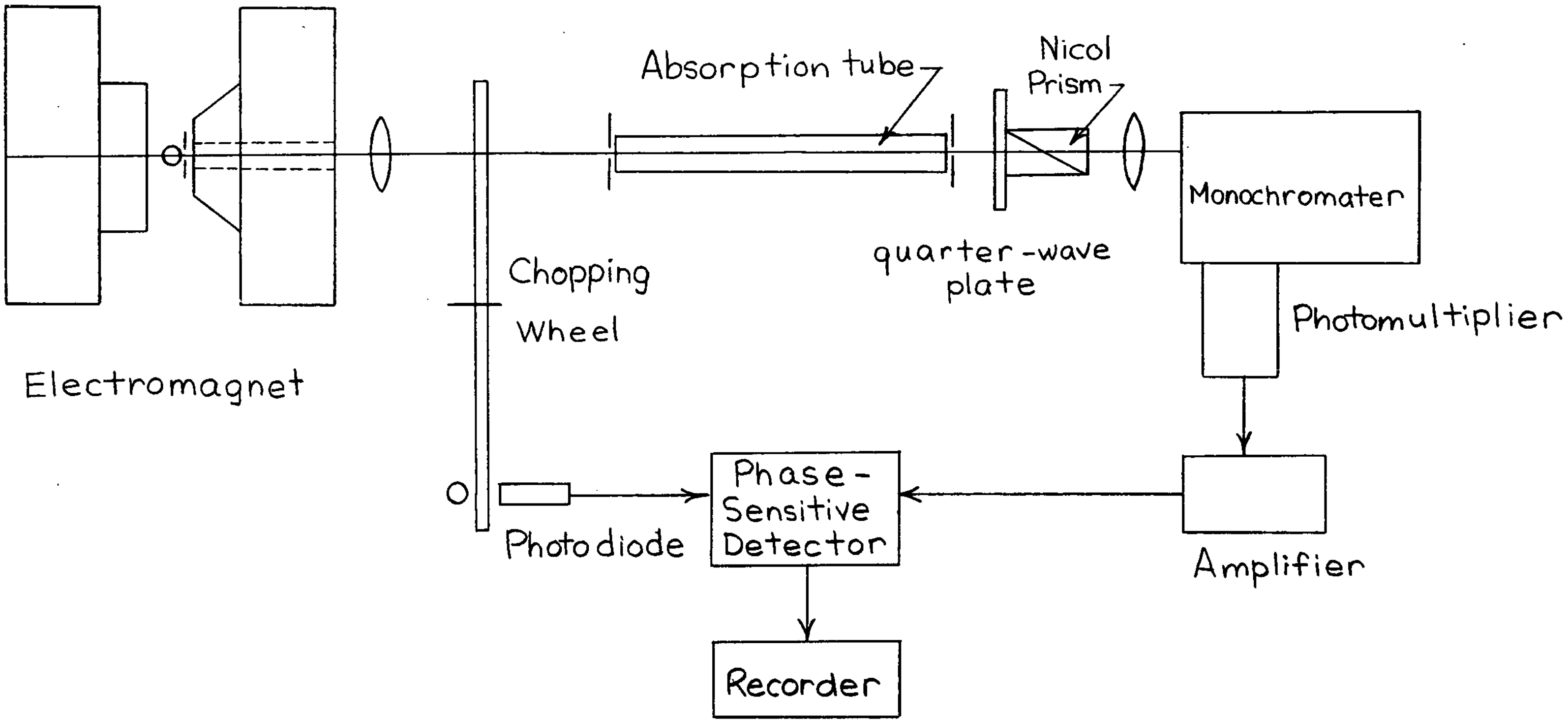
(i) Background Source

The background light source consists of a Neon Geissler tube, placed between the pole faces of an electromagnet. The source was observed through a small hole in one of the pole pieces. This ensures that we are only using the circularly-polarized components which derive from the longtudinal Zeeman effect. The small hole is about 2mm. in diameter, the same as the capillary in the Geissler tube. The variation in magnetic field over such a distance is quite small, having been measured by means of a Hall effect probe to be of the order of 5 gauss or less at the highest current used where the field was about 4 kilogauss. The temporal variation of the field is also quite small and so we feel safe in neglecting the effect of field inhomogeneity as a broadening mechanism.

The pressure of the gas in the Geissler tube was about 10 mm Hg, and at this pressure we find that the Lorentz contribution (which derives from pressure broadening) to have a significant effect on the shape of the emission line, and hence of the transmission curve.

The temperature of the gas in the capillary was

Figure 2 – Experimental Arrangement



measured by using a crude resistance thermometer to be about 67°C (ie 340°K) with a current of 5 ma through the Geissler tube -- the same current value as used throughout the experiment. From theory (7), the temperature is a constant independent of radius.

(ii) Absorption tube

The absorbing medium is the positive column of a low pressure glow discharge in Neon:

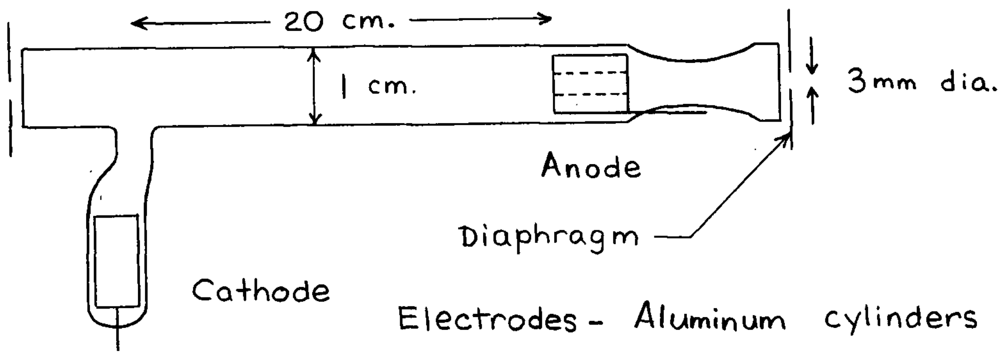


Figure 3 -- Absorption tube

The pressure of the gas in the tube was 2mm Hg, and the current used throughout the experiment was 2ma.

The diaphragms used at each end of the tube had a 3mm diameter hole centered on the axis of the tube. The density of excited states varies little within this radial distance[16].

The tube was viewed through the anode to cut down the abnormal end effects as much as possible.

Under the conditions of the experiment, the absorption line profile is mainly determined by Doppler broadening, with a characteristic temperature of about 295° K.

(iii) Optical System

The light from the background source is directed by a condensing lens through a chopping wheel, through the absorption tube, and is then focused on the slit of a Bausch and Lomb monochromater. The entrance slit was kept just sufficiently large to accept all the light from the source, and the exit slit was made just wide enough to allow all of one line to enter the photomultiplier but to exclude all other lines. The photomultiplier was a Philips model 150 CVP, cooled by dry ice to cut down on the thermal noise.

A quarter-wave plate-Nicol prism combination was used to convert the circularly-polarized Zeeman components to plane polarized and then to select one of these components. This combination was placed after the absorption tube to cut down the amount of radiation from the absorption tube which enters the monochromater, and was aligned to accept the right-circularly polarized component. When the magnet was run in the normal current mode this was the high frequency component.

(iv) Electronic Detection

The amplitude-modulated light beam falling on the photomultiplier photocathode is converted to a pulsating electron current. This current signal is then amplified by a narrow band amplifier, centred on the chopping frequency of 990 cps. This amplified signal and the reference signal are fed into a phase-sensitive detector, and the output of the PSD is shown on a Heathkit chart recorder.

(b) Experimental Procedure

The transmitted line intensity was measured with the phase-sensitive detector as a function of the applied magnetic field. If the intensity is measured both with and without an absorbing medium we can determine the transmission as a function of the frequency shift. The frequency shift is determined by noting the current through the electromagnet, using a calibration curve derived from measurements with a Hall effect probe to obtain the corresponding magnetic field strength, and then using the formulae relating Zeeman splitting to field as given by Back[1].

The resulting transmission profile must then be interpreted in terms of the line profiles of the absorbing medium and the background source. An attempt at interpretation was made by calculating numerically the transmission profile as a function of the absorption and emission line shapes, and trying to fit the theoretical profile to the experimentally determined one. In calculating the theoretical transmission profile, there are several effects which must be taken into account since they have a significant effect:

(i) The presence of two isotopes of Neon -- Ne^{20} and Ne^{22} being the main contributors -- is important. Although the less abundant isotope (Ne^{22}) produces only about 1/10 as much light as the Ne^{20}; this light is absorbed much less strongly. As a result, there are situations when the Ne^{22} radiation is the dominant contribution to the measured intensity. It was found both experimentally and theoretically that the presence of the additional isotope causes the transmission profile to be asymmetrical. To accurately match the theoretical transmission curves to the experimental curves, we must know the isotope separation. For this parameter we used the values quoted by Nagaoka and Mishima[15]:

Table 1 -- Isotope Shifts

λ	$\delta\lambda$	$\delta\sigma$
5852 Å	-.0258 Å	.075 cm^{-1}
6074	-.0206	.056
6163	-.0210	.055
6266	-.0212	.054
6532	-.0240	.056

(ii) The effect of non-Doppler broadening mechanisms on the emission and absorption line profiles is also significant. The main non-Doppler mechanism is pressure-broadening, which can give a Voigt parameter $a=\frac{\Delta\nu_L+\Delta\nu_D}{\Delta\nu_D}$ as large as 0.2 in the case of the Geissler tube.

(iii) The light from the background source will undoubtedly suffer from self-absorption, but quantitatively the extent of this effect may be difficult to take into account. The computational difficulty is due to the radial variation in the density of the emitters and to the cylindrical geometry viewed from the side.

From Chapter II, section (b), we have the expression for the transmission (as a function of frequency) which we must try to calculate:

$$T = \frac{\int_{\text{line}} I_\nu(o)\, e^{-K_\nu \ell}\, d\nu}{\int_{\text{line}} I_\nu(o)\, d\nu}$$, where

$I_\nu(o)$ is the intensity distribution for the background line. Since the background line and the absorption line (given by K_ν) are of comparable widths, we find that the transmission curve is affected by the shape of $I_\nu(o)$. Since this shape can be affected by all the broadening mechanisms, we must try to take them into account.

A programme was set up to calculate the integrals numerically, using Simpson's rule, allowing for functional expressionals for $I_\nu(o)$ and K_ν. For small Voigt a parameters it was found that a perfectly good representation for a Voigt function is a linear combination of Gaussian and Lorentzian functions:

$$V_\nu(a) = a * L_\nu + (1 - a) * G_\nu ,$$

where V_ν is a normalized (to peak = 1) Voigt function, L_ν a similarly normalized Lorentz function and G_ν a Gauss function, where all have the same half width. By taking into account the variation of half width with a change in a, it is in general a simple task to construct a good Voigt function for any small a.

We assume that K_ν is a Voigt function with peak height K_o, and that $I_\nu(o)$ is a self-absorbed Voigt function:

$K_\nu = K_o * V_\nu(a)$, where a is the Voigt parameter appropriate to the absorbing medium, and

$$I_\nu(o) = V_\nu(a^1) * \left[1 - e^{-K_o^1 * V_\nu(a^1) * \ell^1}\right] ,$$

where a^1 is the Voigt parameter appropriate to the emitting medium, K_o^1 is the peak of the absorption coefficient for the emitting medium, and ℓ^1 is the effective depth of the emitting medium, which corresponds to the diameter of the Geissler tube. In the numerical computation we used $\ell^1 = 0.2$ cm, and $\frac{K_o^1}{K_o} = 10$. This was thought to be a fairly reasonable approximation, in the light of our lack of knowledge. We also assumed that the only non-Doppler broadening was that due to pressure, and that this dependence is linear: $a = a_o * P$. Under this approximation we have $\frac{a}{a^1} = \frac{2}{10}$; and so we attempted to obtain a best fit by varying K_o and a^1.

CHAPTER IV

Results

The main results were achieved on measurements of the 6074, 6266 and 6532 Å lines, all of which exhibit the normal triplet pattern but with 6074 having an abnormally large splitting. We also made a few runs on the 5852 Å line, but the absorption was so small that little confidence was placed in the results.

A series of graphs is shown on the next few pages showing the experimental results for the three lines along with the computed transmission profiles which best fit the observed profiles.

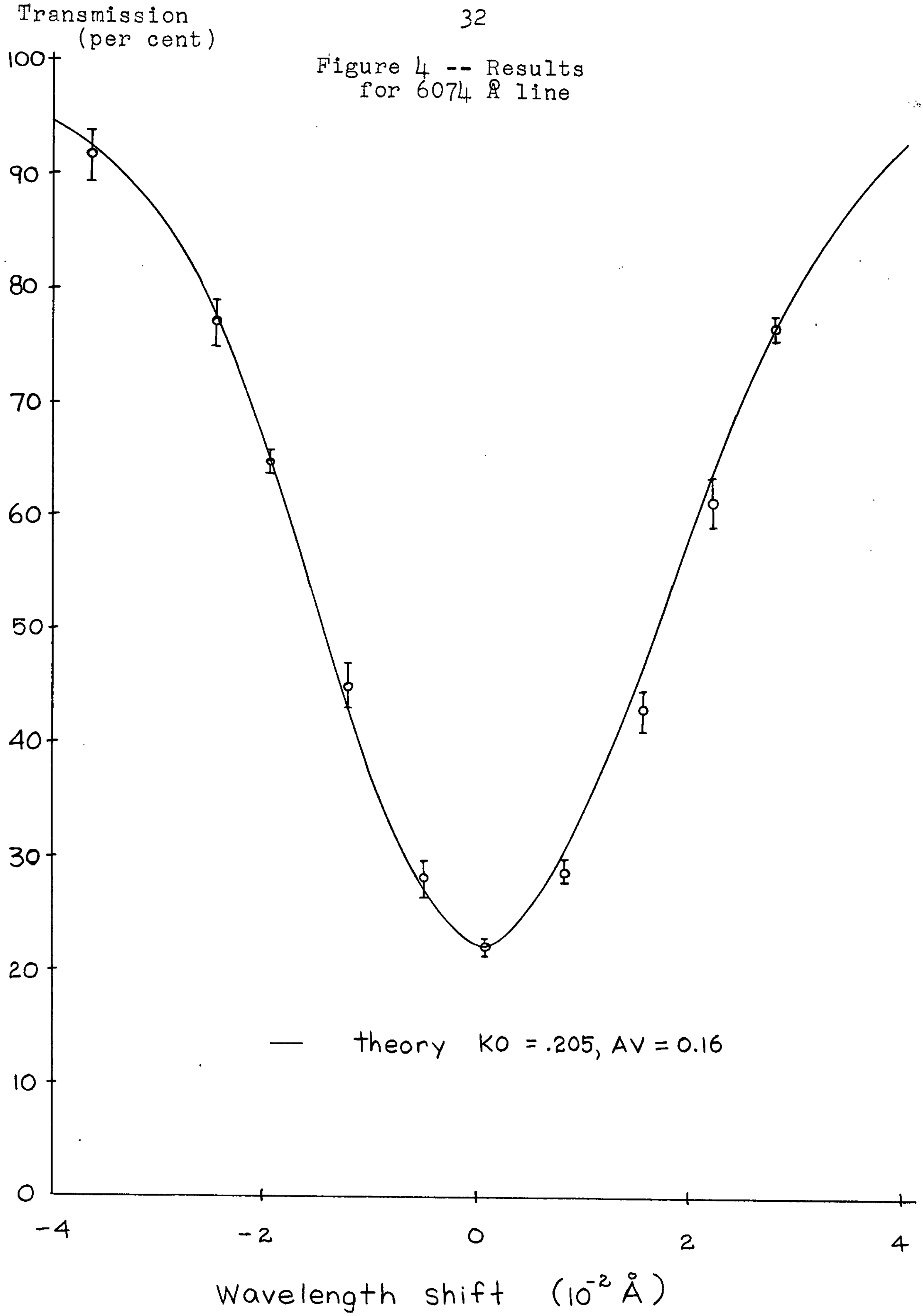
Subject to the approximations outlined in the preceding chapter, I found a best fit for the following parameters:

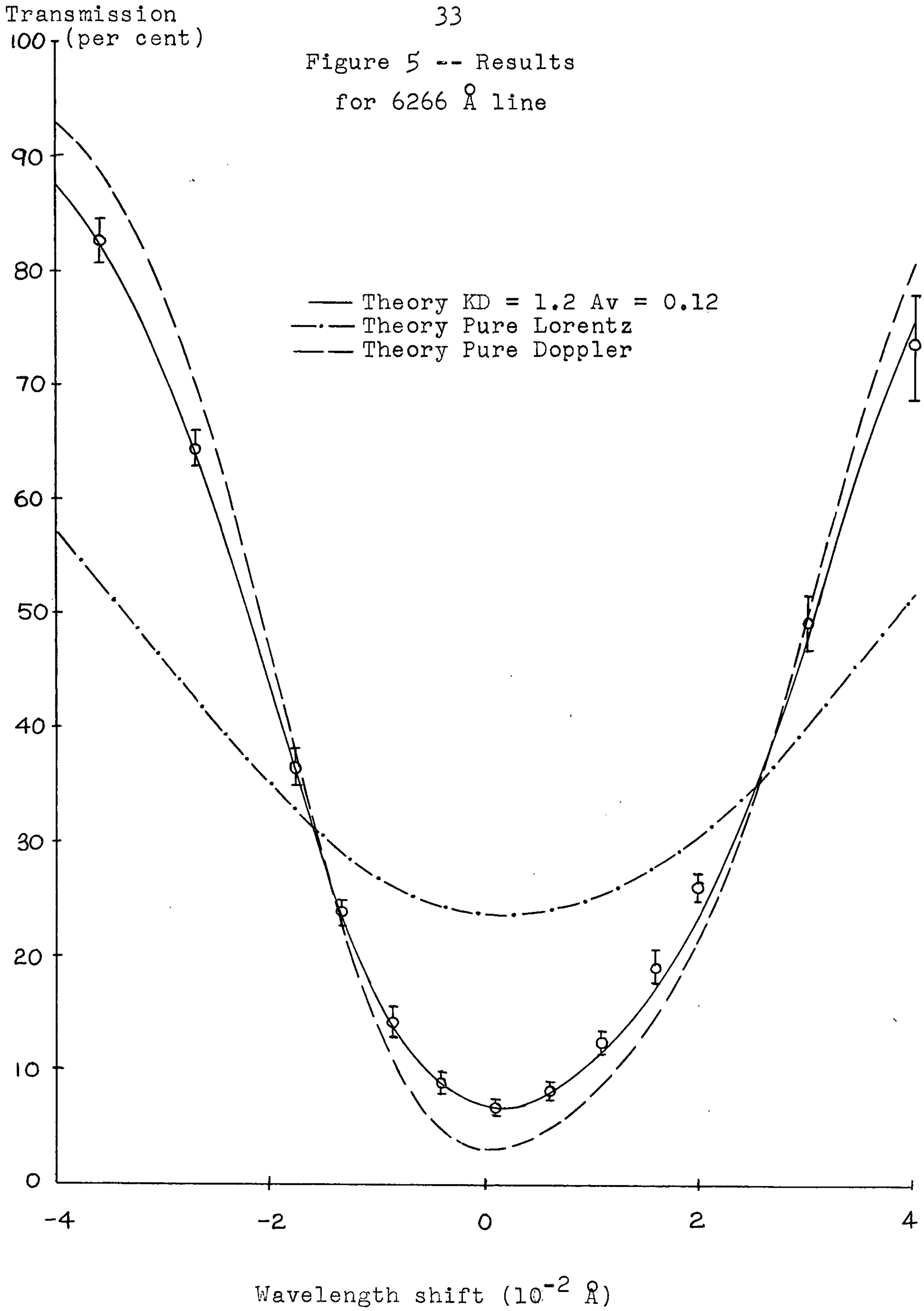
Table 2 -- Results of best fit

	KO	KOdopp	AV	AVA
6074	0.2	0.24	0.26	.034
6266	1.2	1.37	0.12	.026
6532	0.7	0.8	0.12	.026

where KO is the peak height of the Voigt function K_ν, KOdopp is the corresponding "pure Doppler height," AV is the Voigt parameter for the background source and AVA is the Voigt parameter for the absorber.

Figure 4 -- Results for 6074 Å line




Transmission (per cent)
100
90
80
70
60
50
40
30
20
10
0
Figure 5 -- Results for 6266 Å line
Theory KD = 1.2 Av = 0.12
Theory Pure Lorentz
Theory Pure Doppler
-4
-2
0
2
4
Wavelength shift (10^{-2} Å)

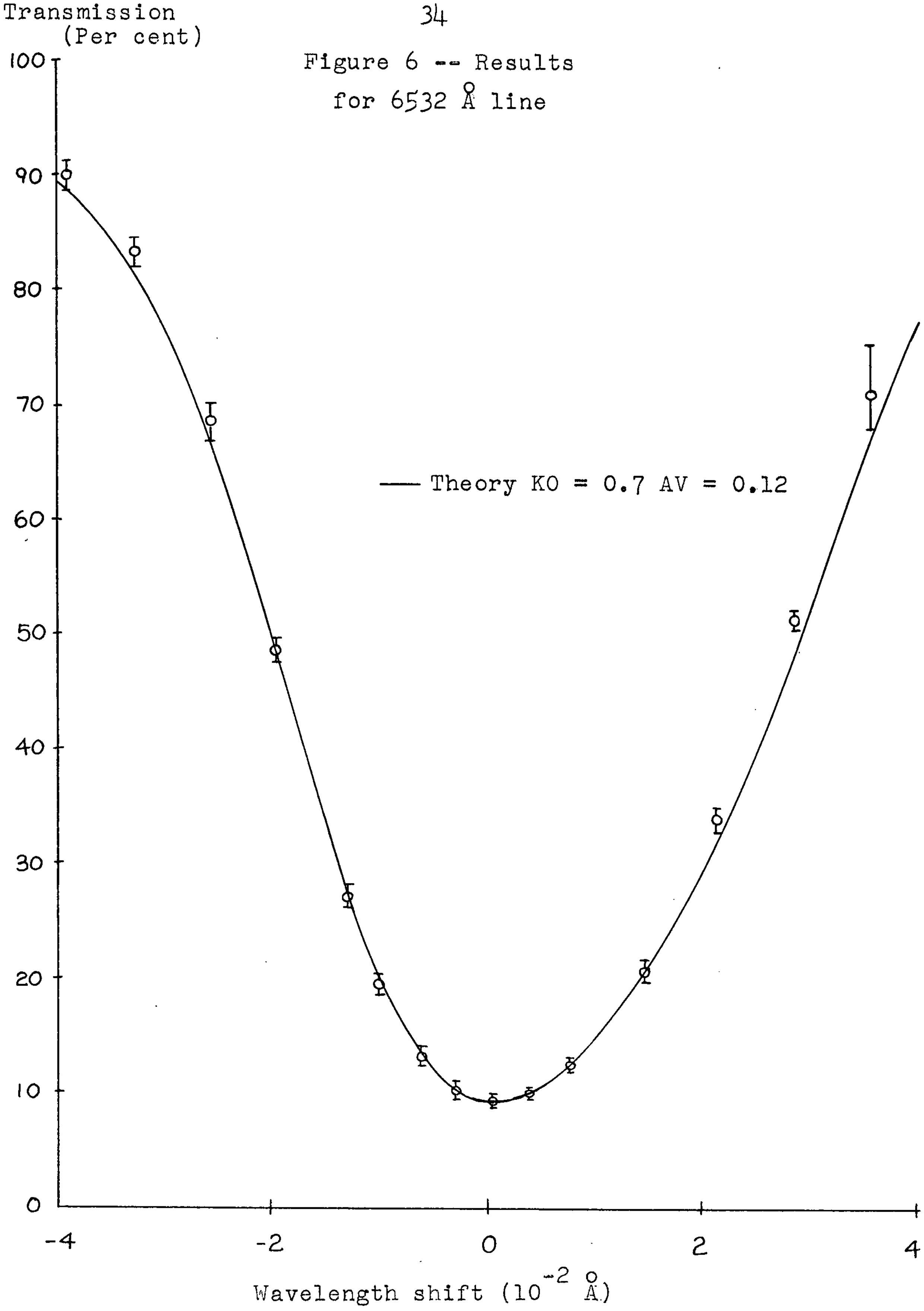


Figure 6 -- Results for 6532 Å line

Since the 6266 Å and 6532 Å lines have the same lower level, we can determine the relative oscillator strength from the relation:

$$\frac{(KOdopp)_1}{(KOdopp)_2} = \frac{\lambda_1}{\lambda_2} \quad frel$$

$$\therefore \quad frel = \frac{(6532)}{(6266)} \quad \frac{1.37}{0.8}$$

$$= 1.78$$

From the results obtained by A. M. Robinson[16], we have

$$frel = \frac{0.334}{0.181} = 1.84$$

This agreement is encouraging.

Comparison

Up until this time the main work on the pressure broadening of Neon spectral lines has been by Lang[13]. He found that most lines in the Neon spectrum showed a similar broadening due to pressure except for the lines which have the S_2 lower level. These lines have a large "collision diameter," most likely because of the strong optical coupling of the S_2 level with the ground state, giving rise to a large perturbation of the lower electronic state (S_2 level). The other optically-coupled level, the S_4 level, is much less strongly coupled*, and so exhibits much less resonance broadening, while the other two levels (S_3 and S_5) are metastable and hence exhibit no resonance effects. The results quoted in this thesis for the Voigt a parameters are about twice as great as would be found by Lang for the same line:

Lang would have a = 0.065 for the 6532 line, whereas I found a best fit for a = 0.12.

I should also note that Connor and Biondi[6], on measuring the pressure broadening of the 5852 line, found a broadening rate twice as great as that quoted by Lang.

I should further note a decided discrepancy between my result for the 6074 line and Lang's results. I found a best fit for this line with a = 0.16, whereas from Lang's results we should have a = 0.033. It appears from Lang's results that the lines with the S_4 lower level do not broaden linearly with pressure. This effect could be the result of some resonance broadening at lower pressures which becomes less important with increasing pressures. This non-linearity could result in a larger value of a for the "S_4 lines" for the low pressures we used.

*See (12) P 250

CHAPTER V

Discussion and Conclusions

(a) Method

The method employed in this experiment would appear to provide a successful means of studying line profiles. It was found possible to fit a theoretical computed transmission curve to the experimental data, and from this to infer approximate values for some of the shape-determining parameters of the line. It should be emphasized that this procedure involved the approximation of various effects:

(i) the isotope shift was assumed to be given by the results quoted by Nagaoka and Mishima[15], and it was further assumed that the amount of light from each isotope was proportional to its natural abundance;

(ii) the gross approximation of the effect of self-absorption in the background source, which can be a large effect;

(iii) the approximation of the lines as Voigt functions involves neglecting the effects of field inhomogeneity in broadening the background line and neglecting any pressure shift which accompanies the pressure broadening;

(iv) the effective temperatures were estimated and so may not be very accurate, but it was found that the transmission curve is not very sensitive to a change in the assumed temperatures.

(b) Results

In the face of these approximations it can only be hoped that the results quoted in this thesis give a fair approximation of the relevant parameters -- the collision diameters. But it is certainly obvious that we cannot investigate the effects of pressure-broadening on the basis of a measurement at one pressure. I feel it is definitely worthwhile to study this more intensively, since the technique employed here provides a good method of studying the shape of narrow spectral lines, and there seem to be many interesting effects in the pressure-broadening of Neon spectral lines.

(c) Future Work

The necessary sequal to this first attempt is to change the experimental conditions so to have the unknown parameters more under control.

Since we would like to study the effects of pressure on the absorption line, we must try to make the effect of the shape of the background line small. This can be helped by making the emission line narrow with respect to the absorption line. The main attack towards making the emission line narrow seems to be in reducing the self-absorption in the background source. This could be accomplished by using a lower pressure source with a small depth of field, so that the opacity is small. This would also tend to reduce the pressure broadening and serve to make the emission line more purely Doppler. As an aid in simplifying the analysis, we could use an isotopically pure gas in the background source so that we would have only one component in the spectrum.

We can also try to make the absorption line broader, either by increasing the Doppler width or increasing the pressure. If we want to study pressure-broadening it would appear that the most likely candidate is the 5852 Å line since it shows a large pressure broadening.

APPENDIX

(a) Determination of Line Profile from Transmission

The transmission function which one observes by such an experiment has been shown to be:

$$T(\Delta\nu) = \frac{\int I(\omega - \Delta\nu)\, e^{-K(\omega)\ell}\, d\omega}{\int I(\omega - \Delta\nu)\, d\omega}$$

where K (ω) describes the absorption line profile, and I $(w-\Delta\nu)$ the emission line profile. Our problem, being to determine K(w) from a knowledge of T $(\Delta\nu)$, requires a knowledge of $I(w-\Delta\nu)$ since this may be considered to be the response function of the apparatus on a measurement of the function $\exp(-K(w)\ell)$. For a δ-function response of the apparatus (i.e. a purely monochromatic source) we find:

$T(\Delta\nu) = e^{-k(\Delta\nu)\ell}$, and hence we can find K(w) directly. But since the background line has a finite width, in fact comparable to the absorption line width, the action of the response function will be to cause a distortion of the measured function.

The response function can be regarded as giving rise to a transformation:

$$T = Tr\left\{ e^{-K(\omega)\ell} \right\}$$

from which it would appear desirable to obtain the inverse (i.e. the deconvolution):

```
$JOB    79266   B STANSFIELD
$TIME           5
$FORTRAN
C TRANS AS FCN OF LINE PARAMETERS
C      BACKGROUND LINE HAS SOME LORENTZ SHAPE
C      INCLUDING SELF ABS IN BACKGROUND
C    INCLUDING THREE ISOTOPES OF NEON
      REAL KO,L
      REAL KOSAB,LGT
      KO=1.2
      L=20.
      WO=-8.
      WN=8.
      EQUIVALENCE(WPRIM,DZ)
      TE=340.
      TA=295.
      H=0.2
      N=80
C   QA IS PURE DOPPLER WIDTH IN .01 ANGSTROM
      QA=0.0995*SQRT(TA)
      QE=0.0995*SQRT(TE)
C AV IS VOIGT PARAMETER
      AV=0.0
      DO 94 M=1,2
      Y=10.
      X=0.2
C   DI IS ISOTOPE SHIFT IN .01 ANGSTROM
      DI=2.12
      AVA=X*AV*SQRT(TE/TA)
      KOSAB=KO*Y
      LGT=0.1
      P=1.-AV
      R=1.-AVA
      PI=3.14159265
C   DD IS WIDTH OF LINE WHEN INCLUDE SOME LORENTZ
      DD=QE*(1.+.635*AV+.15*AV**2)
      DL=DD
      DDI=0.954*DD
      DLI=DDI
      DDA=QA*(1.+.635*AVA+.15*AVA**2)
      DLA=DDA
      DDAI=0.954*DDA
```

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```
      DLAI=DDAI
      DD21=0.977*DD
      DL21=DD21
      DDA21=0.977*DDA
      DLA21=DDA21
      Z=0.
      DPE=Z*AV*QE
      DPA=Z*AVA*QA
C  VOIGT LINE IS REP BY LINEAR COMB OF LORENTZ $ GAUSSIAN
      B(W)=EXP(-(2.*W*SQRT(ALOG(2.))/DD)**2)+
     1  0.1*EXP(-(2.*(W+DI)*SQRT(ALOG(2.))/DDI)**2)+
     2  0.003*EXP(-(2.*(W+DI/2.)*SQRT(ALOG(2.))/DD21)**2)
      C(W)=1./(1.+(2.*(W-DPE)/DL)**2)+0.1/(1.+(2.*(W+DI-DPE)/DLI)**2)
      SAB(W)=P*B(W)+AV*C(W)
      E(W)=1.-EXP(-SAB(W)*KOSAB*LGT)
      D(W)=EXP(-(2.*W*SQRT(ALOG(2.))/DDA)**2)
     1  +0.1*EXP(-(2.*(W+DI)*SQRT(ALOG(2.))/DDAI)**2)
     2  +0.003*EXP(-(2.*(W+DI/2.)*SQRT(ALOG(2.))/DDA21)**2)
      S(W)=1./(1.+(2.*(W-DPA)/DLA)**2)
     1  +0.1/(1.+(2.*(W+DI-DPA)/DLAI)**2)
      F(W)=R*D(W)+AVA*S(W)
      G(W)=EXP(-F(W)*KO*L)
      ASUM4=0.
      ASUM2=0.
      K=1
      W=-8.
    9 ASUM4=ASUM4+E(W+H)
      ASUM2=ASUM2+E(W+2.*H)
      REAL NORM
      IF(K-N+3)12,33,33
   12 K=K+2
      W=W+2.*H
      GO TO 9
   33 NORM=H/3.*(4.*ASUM4+2.*ASUM2+E(W0)+4.*E(WN-H)+E(WN))
      WPRIM=-4.
      DO 44 J=1,21
      SUM4=0.
      SUM2=0.
      I=1
      W=-8.
    7 SUM4=SUM4+E(W+H)*G(W-WPRIM+H)
      SUM2=SUM2+E(W+2.*H)*G(W-WPRIM+2.*H)
```

```
      IF(I-N+3)11,32,32
   11 I=I+2
      W=W+2.*H
      GOTO 7
   32 TRANS =H/3.*(4.*SUM4+2.*SUM2+E(WO)*G(WO-WPRIM)
     1   +4.*E(WN-H)*G(WN-WPRIM-H)+E(WN)*G(WN-WPRIM))
      ATRANS=100.*TRANS/NORM
      WRITE(6,61)AV,KO,DI,WPRIM,ATRANS
   61 FORMAT(2F10.3,3F10.2)
   44 WPRIM=WPRIM+2.*H
   94 AV=AV+1.0
      STOP
      END
$ENTRY
```

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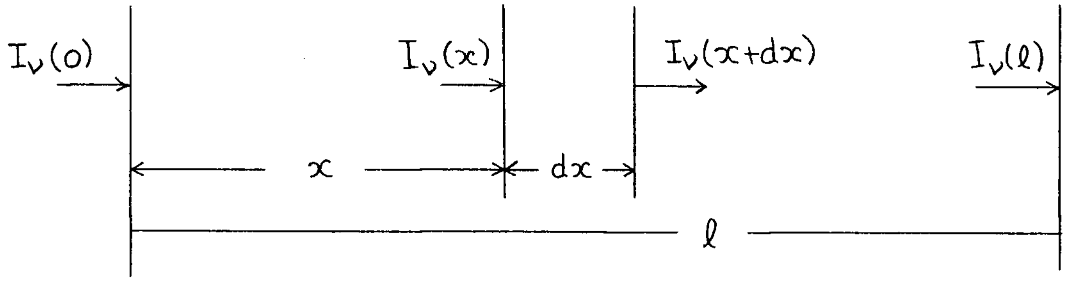
$$e^{-K(\omega)\ell} = Tr^{-1}\{T\} .$$

The determination of this inverse transform is no small task, and in the present experiment the response function $I(w-\Delta\nu)$ is known so poorly that it was deemed desirable to investigate the effect of various parameters -- line shapes, isotope effect, self-absorption -- on the transmission profile. As a result, we used a computer programme employing Simpson's rule of numerical integration to calculate the transmission T as a function of several parameters.

(b) Self Absorption of Spectral Lines

When a beam of radiation travels through a medium, it's intensity will be attenuated if the material is capable of absorving the light.

If we just consider the one-dimensional problem, we have:



$$I_\nu(x + dx) = I_\nu(x)\ e^{-k_\nu(x)dx},$$

where we consider the absorption coefficient to be a function of position.

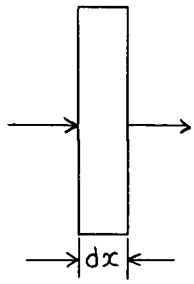
This gives:

$$\frac{d\,I_\nu(x)}{dx} = -\,K_\nu(x)\,dx\,I_\nu(x),$$

and hence:

$$I_\nu(\ell) = I_\nu(o)\,e^{-\int_0^\ell K_\nu(x)\,dx}.$$

If we consider the ratiation from a thermal plasma of temperature T, we must have for each volume element:



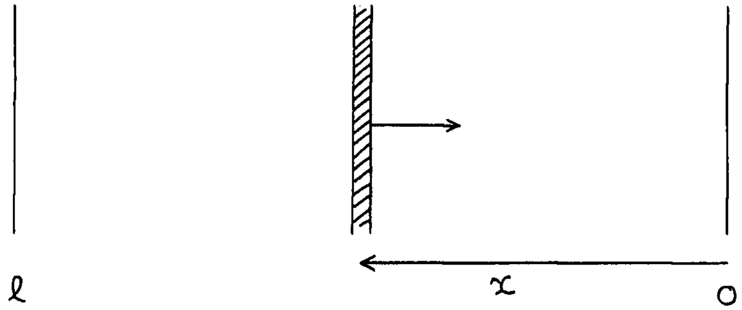
$$I_{dx} = I_o\,e^{-K_\nu dx} \approx I_o(1-K_\nu dx),$$

and hence the absorbed intensity is $I_o\,k_\nu\,dx$.

Since this volume element must also be in thermodynamic equilibrium, we must have the contribtuion beam intensity from this volume element:

$$I_o\,K_\nu\,dx$$

where I_o is the black body intensity.



If this volume element is immersed in the plasma at a distance x from the observing edge, we have the contribution to the observed intensity from this volume element:

$$I_o K_\nu(x)\,dx\, e^{-\int_0^x K_\nu(\xi)\,d\xi}$$

If we now include contributions from all such elements, we have:

$$I_\nu = I_o \int_0^\ell K_\nu(x)\,dx\, e^{-\int_0^x K_\nu(\xi)\,d\xi} .$$

In the case of a perfectly homongeneous plasma, we have:

$$I_\nu = I_o \left(1 - e^{-K_\nu \ell}\right),$$

which approaches a black body intensity distribution as $\ell \longrightarrow \infty$.

To consider the specific case of self-absorption in this experiment, we need only to be concerned with the self-absorption of the background light since for the absorption tube there is no such effect. Since the density of excited atoms is not uniform across the Geissler tube capillary, we need to consider the case where the absorption coefficient depends on position. This is, however, a difficult numerical problem and so I will outline the two stages of approximation we considered:

(i) Homogeneous Plasma

In this case, we saw that the intensity distribution is given by:

$$I_\nu = I_o \left(1-e^{-k_\nu \ell}\right),$$

for a plasma of depth ℓ.

In order to show quantitatively the effect on the line profile, we assumed a pure Doppler line:

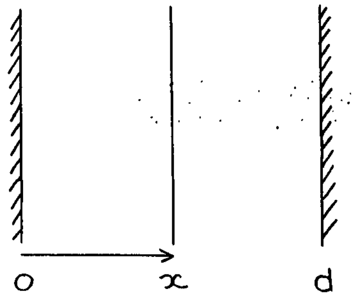
$$K_\nu = K_o \, e^{-\left\{\frac{2\sqrt{\ln 2}\,(\nu-\nu_o)}{\Delta\nu_d}\right\}^2},$$

with a $\Delta\nu_d$ corresponding to T = 340° K. The peak value K_o, was written as 1.2*Y where 1.2 represents the value of K_o for the (axis of the) absorption tube as determined from the experiment (for 6266 line), and Y represents a multiplation factor to take into account the higher density of excited atoms in the Geissler tube compared to the absorption tube.

The function I_ν is shown graphically in Fig. 7 with Y as a parameter and ℓ = 0.2 cm.

(ii) Inhomogeneous Plasma in Slab Geometry

If a plasma is contained between two walls, then we find the density of charged particles to vary as[18]: $\sin\left(\frac{\pi x}{d}\right)$ where:



and the density of charged particles is assumed to be zero at the walls.

Thus, if we observed the plasma through a hole in one of the walls, we would be looking through a highly inhomogeneous plasma.

If we again assume a pure Doppler line, we can write:

$$K_\nu = K_{co} \sin\left(\frac{\pi x}{d}\right) e^{-0.823\,\omega^2} ,$$

where K_{co} represents the peak of the absorption coefficient at $x = \frac{d}{2}$. In order to determine K_{co}, we must somehow relate K_{co} to the K determined experimentally, which is assumed to give a fairly good approx. to the peak of the absorption co-efficient on the axis of the absorption tube. The paper by Ecker and Zöller[7] was taken as showing correct dependence of the charge density as a function of various parameters, and we assume that the excited atom density is directly proportional to the charged particle density. Comparing the absorption tube and the Geissler tube, and using data from (7), we find that

$$\frac{n_c(\text{Geissler})}{n_c(\text{abs. tube})} \approx 68,$$

where n_c (Geissler) is the density of excited atoms on the axis of the Geissler tube and n_c (abs. tube) is the axial density for the absorption tube. Since K_o is proportional to n, we have:

$$\frac{K_{ao}\ (\text{Geissler})}{K_{ao}\ (\text{abs.tube})} \approx 68,$$

where the K_{ao}'s are the axial absorption coefficient peaks.

If we now assume $K_{co} = K_{ao}$, we have

$$K_{co} \approx 68 * K_{ao}\ (\text{abs.tube})$$

and

$$K \approx 68 * 1.2 \sin\left(\frac{\pi x}{d}\right) e^{-.813^{2}}$$

if I consider the 6266 line, say.

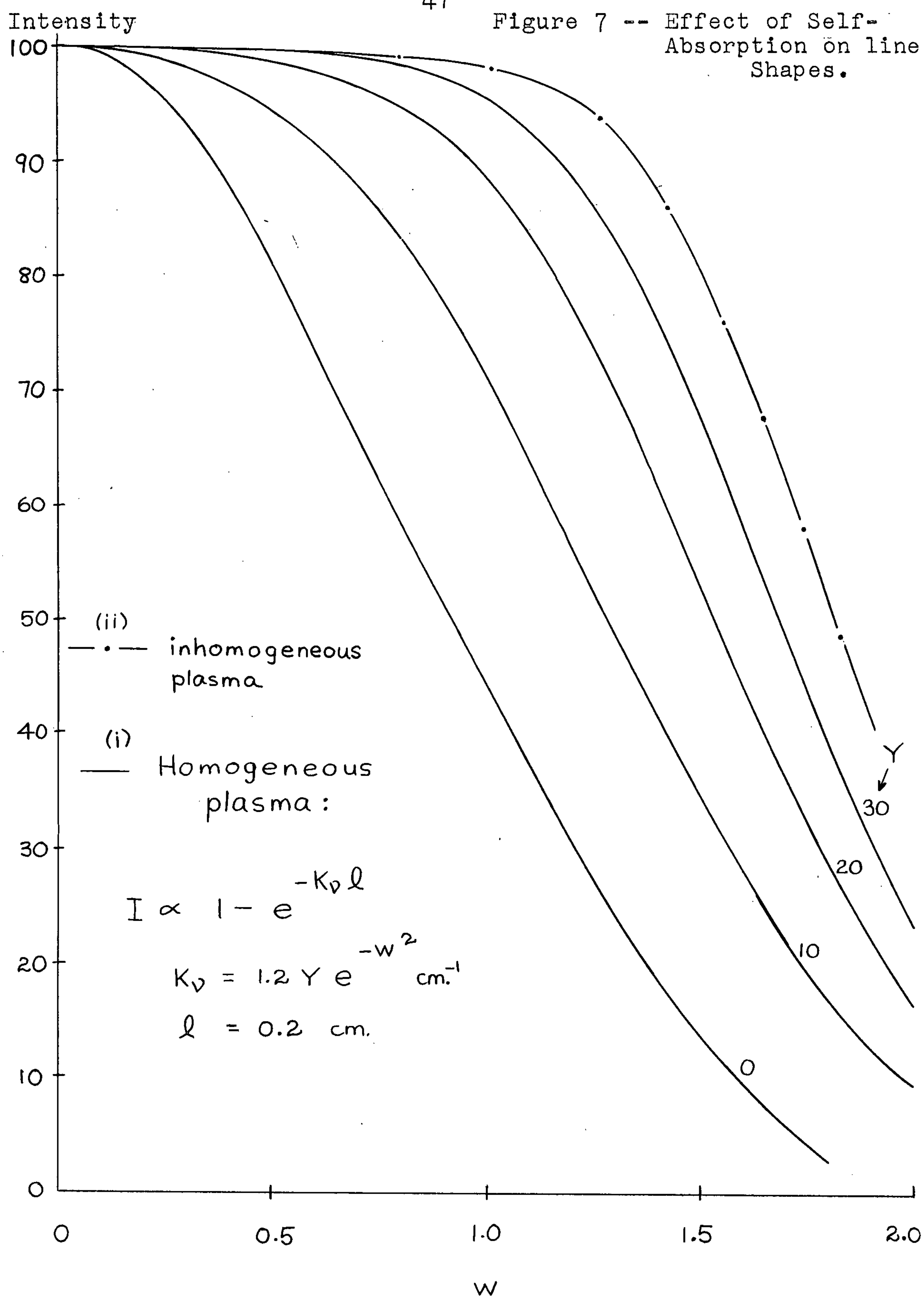
This gives for the line intensity distribution:

$$I_\nu = I_o \int_0^d K_\nu(x)\,dx\, e^{-\int_0^x K_\nu(\xi)\,d\xi},$$

with $K_\nu(x)$ as above.

This function was calculated numerically, and result is shown for d = 0.2 cm. in Fig. 7.

Figure 7 -- Effect of Self-Absorption on line Shapes.



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