APPENDIX A1

A1.1 Design of the Laser Tube

The discharge tube, shown in Figure A1.1, is identical to that developed by Grace (1978) who based his design on that of Piper and Webb (1973). The cathode was constructed from 25 mm diameter type 304 stainless steel bar through which a 4 mm diameter bore had been drilled. Fourteen sidearms, each of 10 cm length, were welded to the main tube section to give an interanode separation of 4 cm. As shown in Figure A1.2 adjacent anodes were placed at 90^0 to each other to allow ease of construction.

A bellows was used at one end of the discharge tube to compensate for thermal expansion of the main stainless steel tube ($\sim$4 mm at 400^0C) thus allowing the Brewster windows, vacuum fittings and discharge axis to maintain a fixed position.

Helium is admitted at the centre of the tube through an oven containing cadmium and the cadmium seeded gas then flows through the discharge volume. Figure A1.3 shows the design of the region used to terminate the active volume. The 4 cm long removable ceramic tube within the heated region defined the end of the discharge. A larger diameter ceramic tube was in part water cooled so that the cadmium metal was condensed from the gas mixture as it passed from the discharge. The large distance of this collected material from the outermost anode eliminated the possibility of the discharge arcing to the cadmium and causing re-evaporation. To facilitate periodic removal and cleaning of the ceramic inserts the endpiece was terminated with Edwards vacuum "O" ring fittings.

The design of the central oven region is shown in Figure A1.4. The central region of the tube and the top section of the oven were constructed from one section of stainless steel to minimize welded joints. A Varian "Conflat" flange welded to the base of the oven structure permitted easy access to the receptacle containing the metal without the need to remove the oven heater. Entry of the gas from the oven region to the active volume was made through a series of 1 mm diameter, 5 mm long holes located in a threaded section at the top of the oven. This design feature was found to be necessary to stop discharge arcing into the oven. An additional design feature of the oven was that the helium gas was premixed with the metal vapour prior to entry of the laser channel. Grace (1978) found that premixing doubled the output power of the laser.

In order to obtain optimal performance of the laser careful consideration must be given to the position and placement of the anode pins. It was found, by Grace, that if the anode was inserted flush with the tube bore and the anode pin tip not enclosed then the glow discharge simply ran between the closest section of the cathode surface and the tip. On the other hand, if the anode insulation was inserted flush with the cathode and the anode recessed further than 10 mm into the insulation the discharge was difficult to strike. It was found that recessing the tip 2 mm into the insulation material was sufficient to prevent short circuiting between the anode and cathode while at the same time permitting easy striking of the discharge. Also, to ensure uniformity of the discharge the ceramic insulation was inserted a distance of 0.1 mm into the active volume. This was done by supporting the insulation on a 3.9 mm precision rod for the setting period of the epoxy used to seal the anodes in position.

The hollow cathode laser

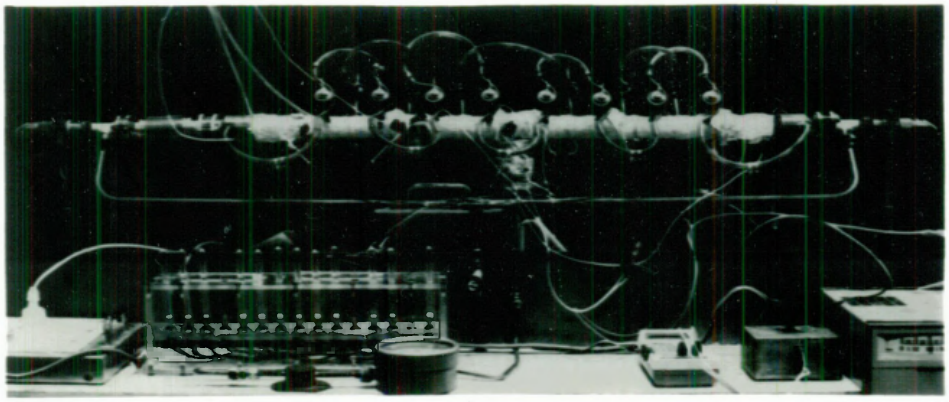

Figure A1.1 Side view

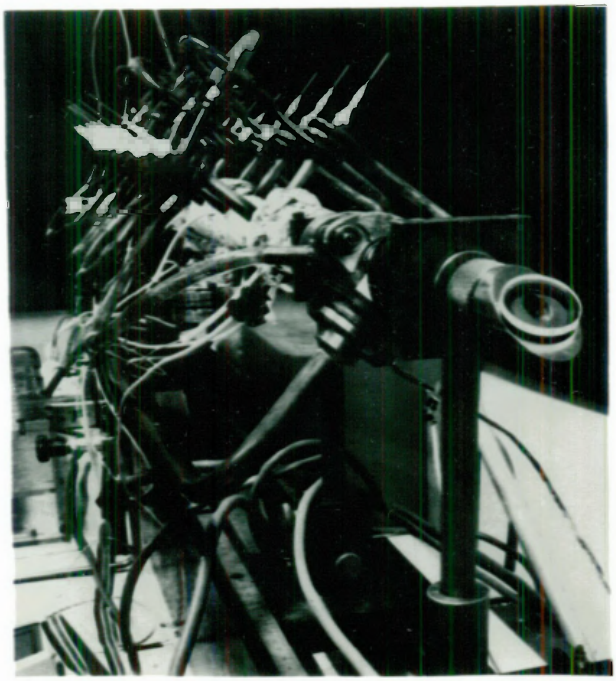

Figure A1.2 End view

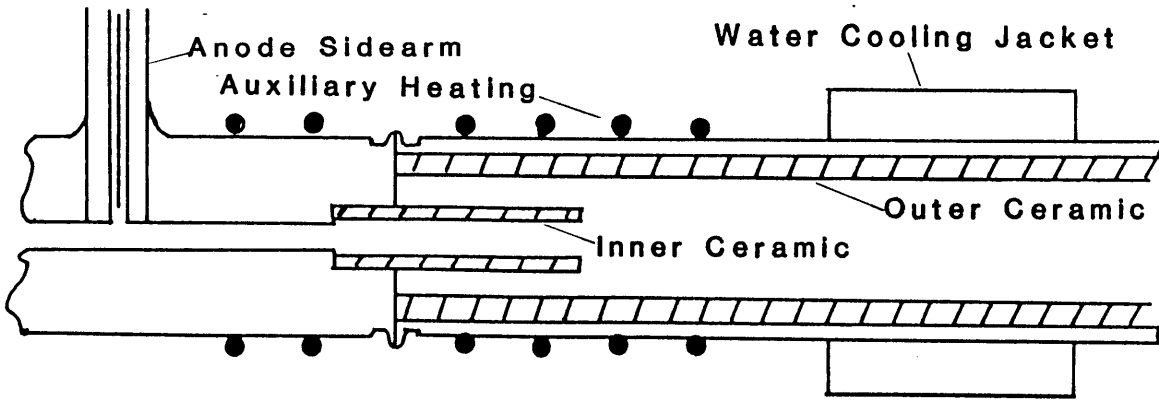

Figure A1.3 Design of the endpiece of the laser tube

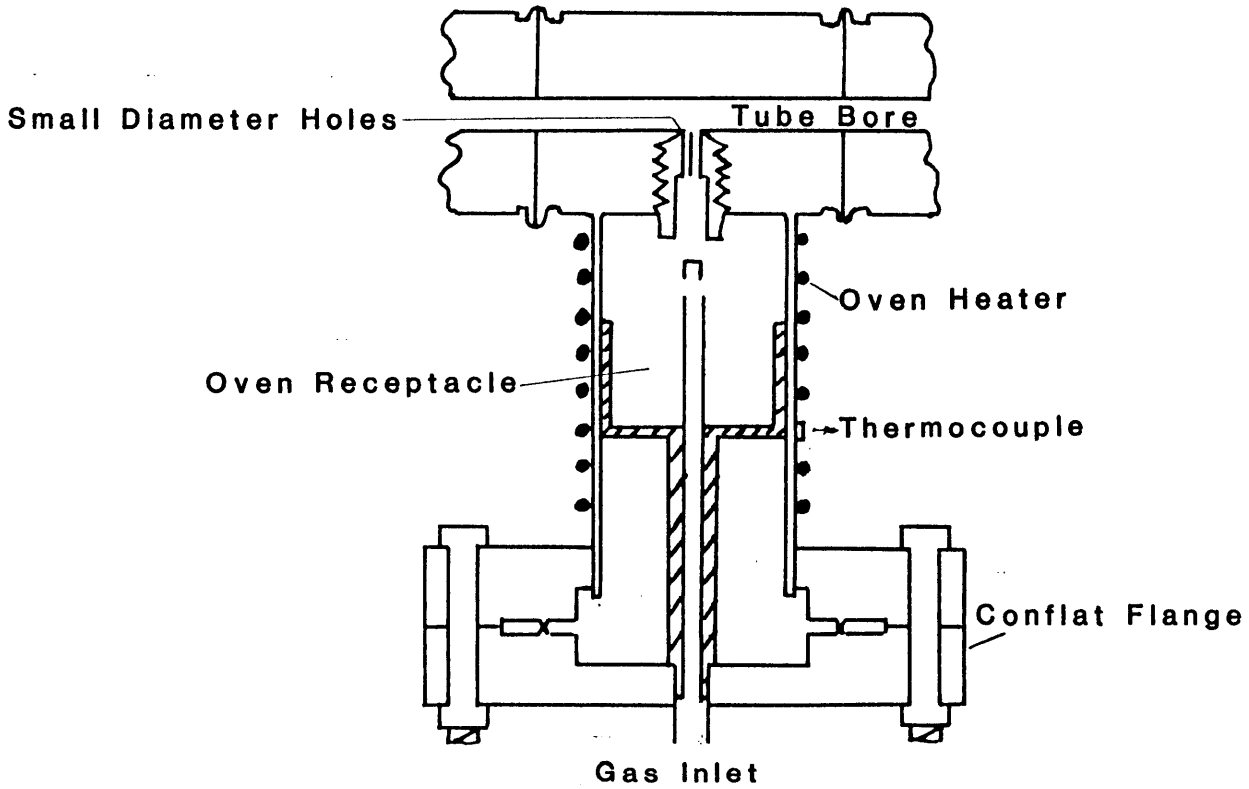

Figure A1.4 Design of the oven section of the laser tube

The anodes were constructed from 2 mm stainless steel rod and insulated from the cathode by ceramic tubing.

All vacuum fittings, with the exception of the conflat flange on the oven, were designed for "O" ring sealing and allowed for ease of construction and dismantling of the discharge tube when periodic cleaning was required. To seal the anodes to the sidearms a low vapour pressure epoxy, Torr seal, was used. Because of the thick walled tubing used in the construction of the discharge tube, water cooling was required at the ends of the anode sidearms in order to prevent failure of the Torr seal joints.

The laser tube and optical components were mounted on a 2 m double rail optical bench (P.T.I. model 2081).

Cadmium metal, of natural isotopic abundance, was used throughout the experiments.

A1.2 Vacuum and Gas Handling System

The vacuum system was constructed from 17 mm internal diameter stainless steel tubing with Viton "O" ring seals and 24 mm Edwards diaphragm values. The system was pumped with a 30 l min^{-1} 2 stage rotary pump (Dynavac 2). An 8 l s^{-1} Vacion pump was used in conjunction with a liquid nitrogen trap to obtain base pressures and assist in leak detection. Base pressures of 10^{-3} Torr were regularly obtainable with the rotary pump and down to approximately 5 x 10^{-6} Torr with the Vacion pump and liquid nitrogen trap.

Intermediate pressure values were measured with an Edwards Pirani gauge (model 8/2) and normal helium operating pressures were read from a 0 - 100 Torr Edwards capsule gauge.

Gas flowed slowly through the discharge tube with the rate of flow being controlled by an Edwards needle valve on the inlet side and a Nupro series L fine metering valve on the pumping side of the system. Flow rates were determined from the volume of water displaced from an inverted measuring cylinder by the helium flowing from the outlet of the vacuum pump.

A1.3 Electrical Considerations

The discharge was run with a 0-2 kV, 0-5 A d.c. power supply with 5% regulation and 1% Ripple (Hippotronics model 802-5A). To ensure a uniform current distribution amongst the 14 anodes each anode was separately ballasted by two 10 kΩ, 75W resistances arranged in parallel. Small toggle switches in series with the anodes enabled individual anodes to be switched on or off.

To prevent condensation of the cadmium metal on the inner (small) ceramic, approximately 150W of electrical heating was required at the ends of the discharge tube.

The external wall temperature was monitored at intervals along the tube with chromel-alumel thermocouples. Under most conditions discharge heating kept the tube body at a higher temperature than that of the oven. When this was not the case, auxiliary heating coils were wrapped along the laser tube and insulated with asbestos and aluminium foil.

A chromel-alumel thermocouple, placed as shown in figure A1.4, provided the temperature sensing element for an Eurotherm temperature controller which kept the oven temperature to within $\pm 1^0$C of the required valu

A1.4 Brewster Windows

The Bewster windows used in all experiments were 25 mm diameter, 3.2 mm thick Schlieren and strain free fused silica with surface flatness of $\lambda/20$ and surface parallelism of 1 second of arc.

APPENDIX A2

A2.1 Introduction

In order to determine the Penning collision rates and calculate the absolute number densities from absorption the gas temperature of the plasma is required. In particular, the parametric variation of the gas temperature with oven temperature, helium pressure and discharge current must be determined.

A2.2 Theory and Experimental Method

The general theory of determining the gas temperature from a spectroscopic study of the intensities of rotational lines in a band may be found in such texts as Herzberg (1950, section IV 4b) and Marr (1968, section 11.6). Its application to the first negative system of nitrogen was developed by Phillips (1973).

The nitrogen used in this study was present as an impurity in the discharge volume with a partial pressure estimated to be $<10^{-3}$ Torr. The first negative system of nitrogen was studied because this system, being a Σ-Σ transition, has a relatively simple rotational structure and is one of the more prominent systems in a hollow cathode discharge when there is an excess of helium. In particular the 3914 Å N_2^+ $B^2\Sigma_u^+ - X^2\Sigma_g^+$ O-O band was investigated.

The branches of a $^2\Sigma$-$^2\Sigma$ transition are classified in the following way. Firstly, the branches for which $\Delta J = -1$, 0 and +1 are designated P, Q and R respectively (J is the rotational quantum number). Secondly, the P and R branches are actually doublets with components $J = K - \frac{1}{2}$ and $J = K + \frac{1}{2}$ (distinguished by subscripts 1 and 2 respectively). Finally, there are two Q branches resulting from transitions with $\Delta K = -1$ and +1. Although the rotational structure of a $^2\Sigma$-$^2\Sigma$ band comprises these six

components, the lines for the R_1, R_2 and Q_{12} branches are so closely grouped in wavelength that they were not resolved by the available spectrometer and thus can be collectively denoted by R. Similarly the three branches P_1, P_2 and Q_{21} will be denoted by P.

From Phillips (1973), the relationship between the photon emission $[Q_K(R)]$ of a line of the R branch, with initial quantum number K, and the gas temperature can be written as

$$\ln\left[\frac{Q_K(R)}{K}\right] = -\frac{hcB_0}{kT_g}\,K(K+1) + \ln\,(N_0\emptyset_K) \qquad \text{(A2.1)}$$

where hc is the Planck constant multiplied by the velocity of light and $B_0\ K(K+1)$ is the rotational term value with B_0 a constant with value

$$B_0 = 0.2083\ \text{mm}^{-1}$$

and $\emptyset_K$ is the statistical weight associated with nuclear spin. In the case of nitrogen, the value of $\emptyset_K$ for odd K is twice the value for even K and the rotational lines alternate in intensity.

Thus the gas temperature can be found from the slope of a graph of $\ln\,[Q_K(R)/K]$ against $K(K+1)$. Because of the term $\emptyset_K$, there are actually two straight lines with different intercepts for odd and even K but the slope is the same for both and hence the gas temperature can be determined from either.

The above discussion was confined to the R branch as these lines are well separated in wavelength for all values of K and hence identification is easy. On the other hand, the wavelengths of the lines of the P branch first converge (to the band head) then reverse as K increases. Near the convergence limit identification was impossible.

Another complication arises because an examination of the P branch wavelengths, measured by Coster and Brons (1932), shows that the lines

arising from the upper level K + 25 coincide in wavelength with the R branch line of level K (within the resolution of the spectrometer) and will affect the result especially at high gas temperatures. To overcome this difficulty Phillips adopted the following approach.

The intensity at a wavelength of the K^{th} line in the R branch is

$$Q_K = Q_K(R) + Q_{K+25}(P)$$

which is given by

$$\ln [Q_K/\bar{K}] = -\frac{hcB_0}{kTg} K(K+1) + \ln (N_0 \phi_K) \qquad (A2.2)$$

where

$$\bar{K} = K + \frac{\phi_K + 1}{\phi_K} (K+26) \exp\left[\frac{-hdB_0}{kT_g} 5O (K+13)\right] \qquad (A2.3)$$

A first approximation to T_g is obtained from equation (A2.1), then $\bar{K}$ is calculated from A2.3 and a more accurate value of T_g is obtained from the graph of $\ln[Q_K/\bar{K}]$ against K(K + 1).

To measure the rotational structure of the $N_2^+(B^2\Sigma_g^+ - X^2\Sigma_g^+; v^1 = O, v^{11} = O)$ band the following experimental method was used. The endlight intensity from the hollow cathode was monitored by a photomultiplier after passing through a spectrometer (SPEC 1.75 m scanning spectrometer model 1320). As the intensity at 3914 Å was weak, the endlight intensity from the discharge was chopped (Roffin model 7500) and the output of the photomultiplier monitored by a phase sensitive detector (Princeton Applied Research Lock-in Amplifier model 128 A). The output of the lock-in amplifier was displayed directly onto a chart recorder.

A typical chart record of the rotational structure is reproduced in Figure A2.1 together with an identification of the rotational lines

of the R branch. The convergence of the P branch to form the branch head is clearly seen and so is the intensity alternation mentioned earlier. Figure A2.2 shows the corresponding graph of $\ln[Q_K/\bar{K}]$ versus $K(K + 1)$. As discussed earlier, the two lines shown on Figure A2.2 correspond to the odd and even K values with the upper line associated with the odd K values.

A2.3 Results and Discussion

The gas temperatures in a "pure" helium discharge operating at different pressures and currents were determined by analysing the rotational spectrum recorded at each pressure and current. Following the procedure described in section A2.2 the coefficient of $K(K + 1)$ in equation A2.1 was computed and the gas temperature deduced from it. With this estimate of Tg the parameter $\bar{K}$ was calculated (equation A2.3) and a graph of $\ln[Q_K/\bar{K}]$ versus $K(K + 1)$ drawn (Figure A2.2). From the value of the slope of the resulting straight line a more accurate value for the gas temperature, taking into account the P branch overlap, was obtained.

Results of the experiment, showing the gas temperature variation with current and pressure, are shown in Figures A2.3 and A2.4. As can be seen from Figure A2.3, for a constant helium pressure, the gas temperature increases linearly with discharge current whereas for a constant current no systematic variation with pressure was observed.

An attempt was made to measure the gas temperature in a He-Cd discharge using this experimental technique but the presence of the strong cadmium spectrum made measurement by this method impossible. However, when cadmium is added to the discharge volume the gas temperature might be expected to increase slightly. This results from the fact that, as cadmium is added to the discharge, in order to maintain a constant current the tube potential

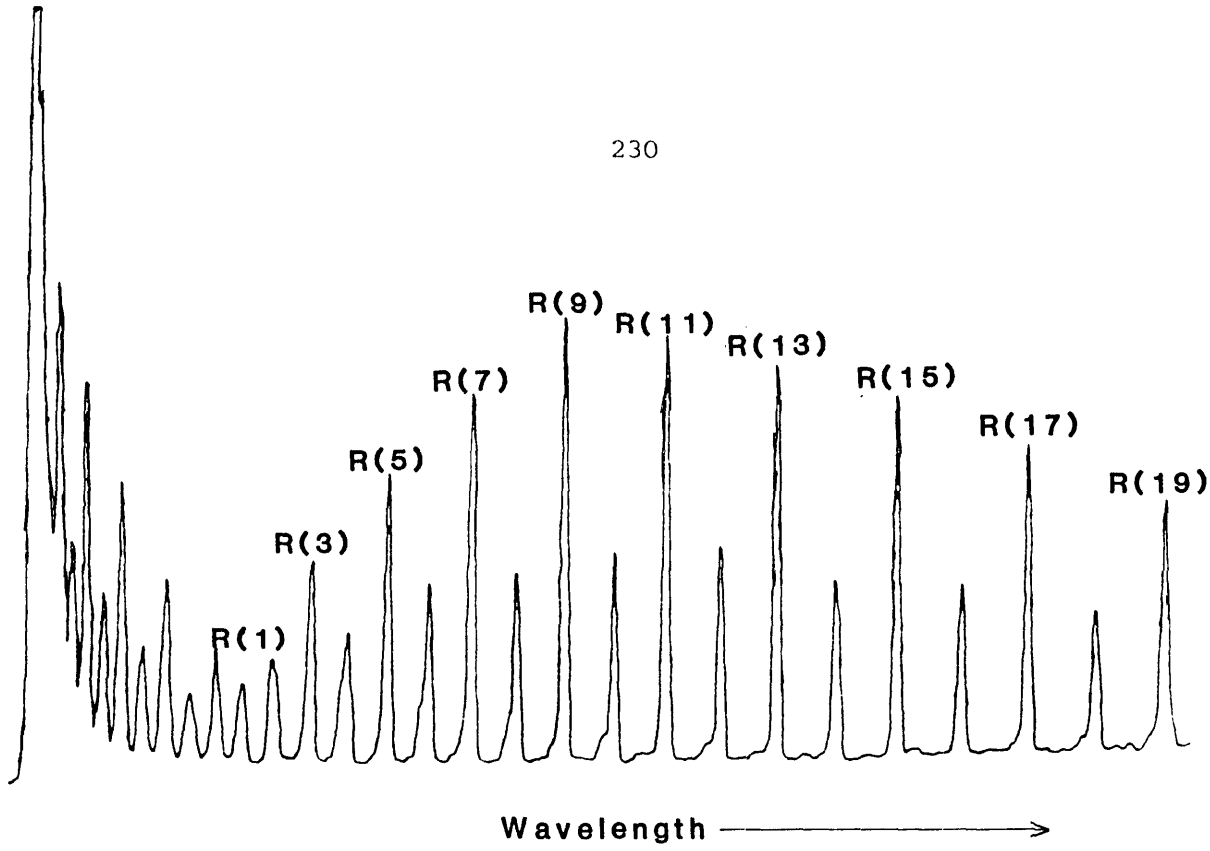

Figure A2.1 A typical chart record of the rotational structure of the O-O band of the N_2^+ (B-X) system

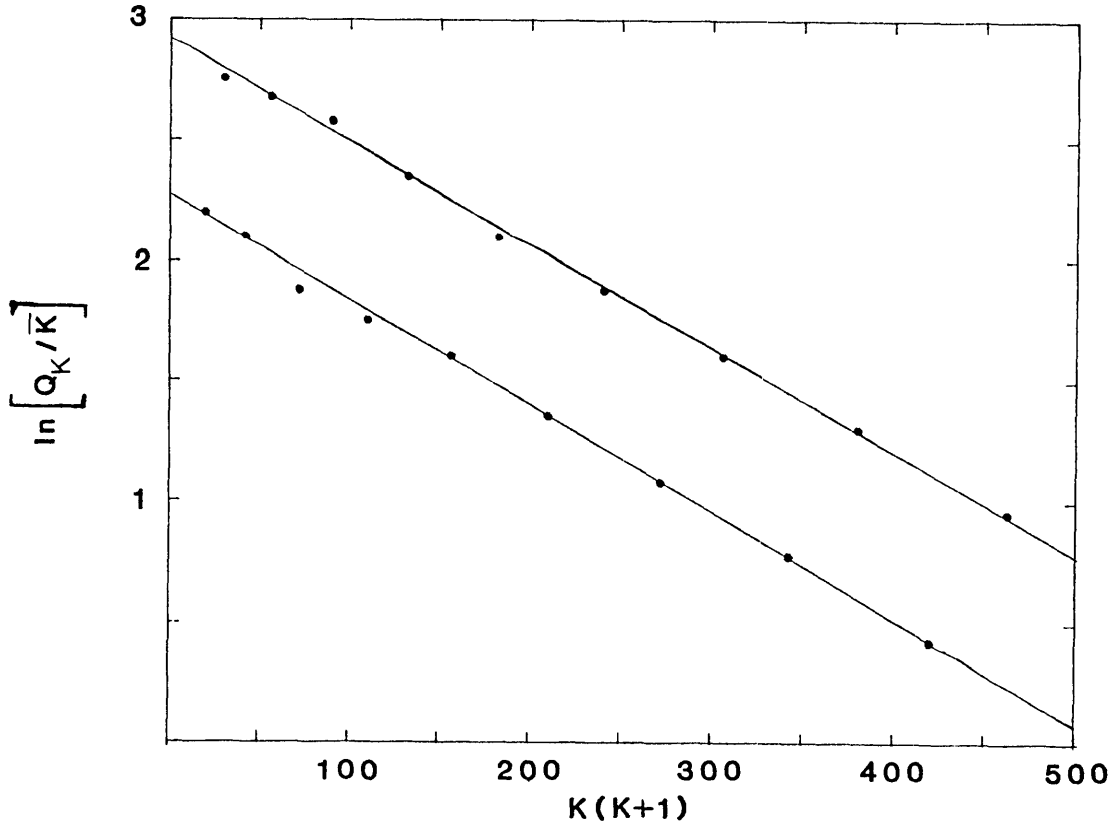

Figure A2.2 Graph of ln $\left[Q_K/\bar{K}\right]$ versus K(K + 1) for calculation of the gas temperature

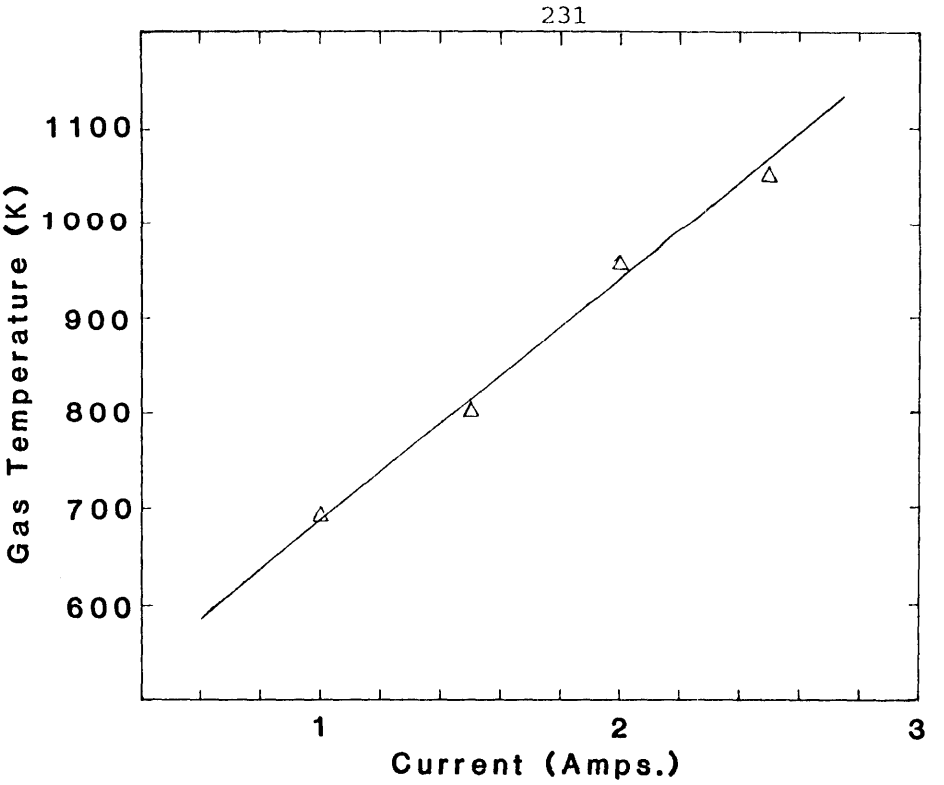

Figure A2.3 Plot of the measured value of the gas temperature versus discharge current in a "pure" helium hollow cathode discharge at a constant pressure of 20 Torr

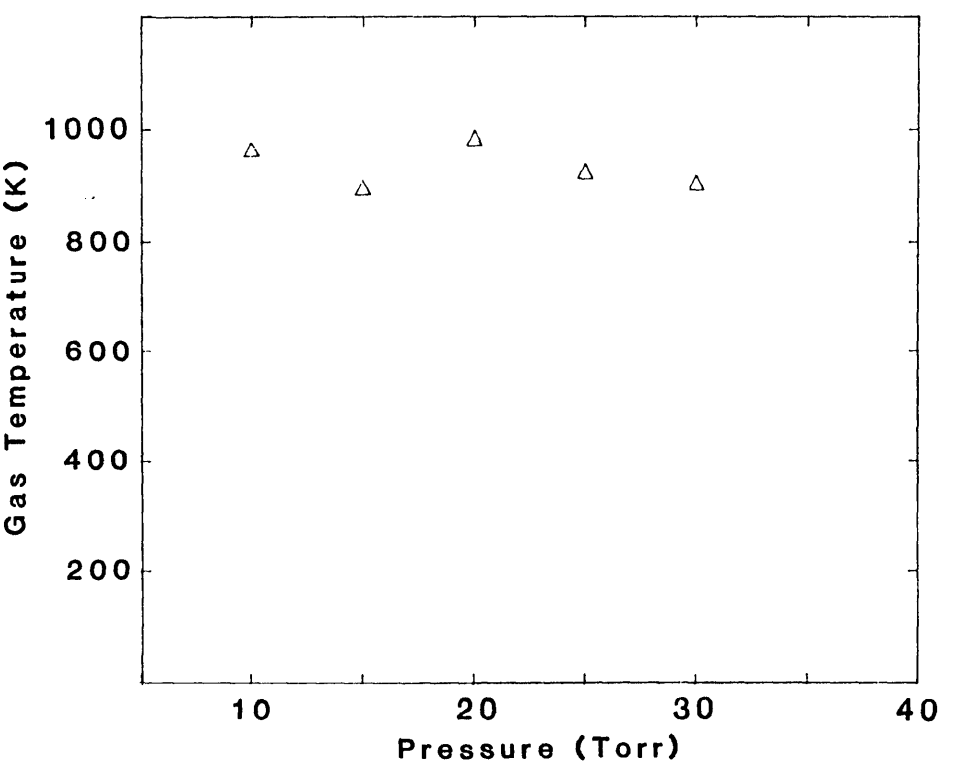

Figure A2.4 Plot of the measured values of the gas temperature versus helium pressure at a constant current of 120 mA/anode

increases ($\sim$10%). Thus adding cadmium results in an increased electrical power input to the discharge and hence to an increase in the gas temperature.

APPENDIX A3

A3.1 Introduction

The fractional absorption technique cannot be used to measure the cadmium neutral density as the absorption occurring in the non discharge region has not been accounted for. In this Appendix an alternative technique is developed accounting for the absorption in both the glow and non glow regions.

A3.2 Theory

A schematic diagram, outlining the concepts and symbols used in the analysis, is given in Figure A3.1.

From section 2.3.1, the light intensity/unit frequency range from the discharge of length l associated with anode 2 is

$$\delta I(\nu)_{em} = \frac{I_0}{k_0} \, d\nu \, [1 - \exp(-k_0 l e^{-\omega^2})]$$

[Anode 2 is the anode second nearest to the detectors.]

Anode 1 is not used in this argument as the ceramic inserts (Appendix A1) limit the discharge length l. Placed between the emitting plasma and the detector is a region containing cadmium atoms homogeneously distributed throughout the volume. This region will heavily absorb the 3261 Å wavelength light and thus the intensity/unit volume reaching the detector is

$$\delta I(\nu)_{det} = \frac{I_0}{k_0} \, d\nu \, [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 d e^{-\omega'^2}] \quad \text{(A3.1)}$$

where d is the length of the absorbing region between the end of the glow discharge and the point of collection of the cadmium vapour out of the He-Cd gas mixture.

Thus the total light intensity received at the detector is

$$I(\nu) = \frac{I_0}{k_0} \int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 d e^{-\omega'^2}] \, d\nu \qquad (A3.2)$$

As it is not possible to evaluate equation (A3.2) directly as the form of I_0 is not known, the following procedure was adopted.

For an identical spectral input the intensity ratio for two different absorption lengths d and d_1 can be expressed as

$$\frac{I_1(d)}{I_2(d_1)} = \frac{\int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 d e^{-\omega'^2}] \, d\nu}{\int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 d_1 e^{-\omega'^2}] \, d\nu} \qquad (A3.3)$$

In the above discussion it has been assumed that the k_0 values of the emitter and absorber are identical, i.e. the ground state cadmium density is the same in the discharge and non discharge regions.

If the intensity from anode 3 is associated with the parameter $I_2(d_1)$ then

$$d_1 = d + 4 \text{ cm}$$

as adjacent anodes are separated by 4 cm and thus we obtain

$$\frac{I_1(d)}{I_2(d_1)} = \frac{\int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 d e^{-\omega'^2}] \, d\nu}{\int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 (d + 4) e^{-\omega'^2}] \, d\nu} \qquad (A3.4)$$

To improve the experimental accuracy, the intensity ratio can be recorded as a function of anode number, and thus a general expression relating the intensity from anode 2 to the intensity from anode n is

$$\frac{I_1(d)}{I_2(d_n)} = \frac{\int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 d e^{-\omega'^2}] \, d\nu}{\int_0^{\infty} [1 - \exp(-k_0 l e^{-\omega^2})] \exp[-k_0 (4xn + d) e^{-\omega'^2}] \, d\nu} \qquad (A3.5)$$

where n = anode number - 2.

In equation (A3.5) the parameters ω and ω', associated with the emitter and absorber respectively, have been distinguished to account for the different Doppler widths of these two regions, the Doppler width of the emitter being determined by the gas temperature data of Appendix A2 while the Doppler width of the absorber is determined by the cathode wall temperature ($\sim$620 K) which is much less than that of the plasma.

Equation (A3.5) was evaluated numerically and a typical result showing the calculated intensity ratio as a function of both anode number (or distance from the spectrometer) and $k_0 l$ is given in Figure A3.2. In evaluating equation (A3.5) the isotope shift and hyperfine structure of the 3261 Å line have been taken into account.

A3.3 Experimental Method and Results

Using the optical system described in section 2.2 the intensity ratio was recorded as a function of anode number and oven temperature. The other discharge parameters of current and pressure were maintained at a constant value. The measured intensity ratios were then compared with the theoretical values calculated from equation (A3.5) for the corresponding experimental conditions. The theoretical curve of $k_0 l$ versus anode number giving the best fit to the experimental result was found and the corresponding ground state density evaluated using equation (2.6).

The results of the experiment, showing the measured cadmium neutral density as a function of oven temperature, are listed in Table A3.1.

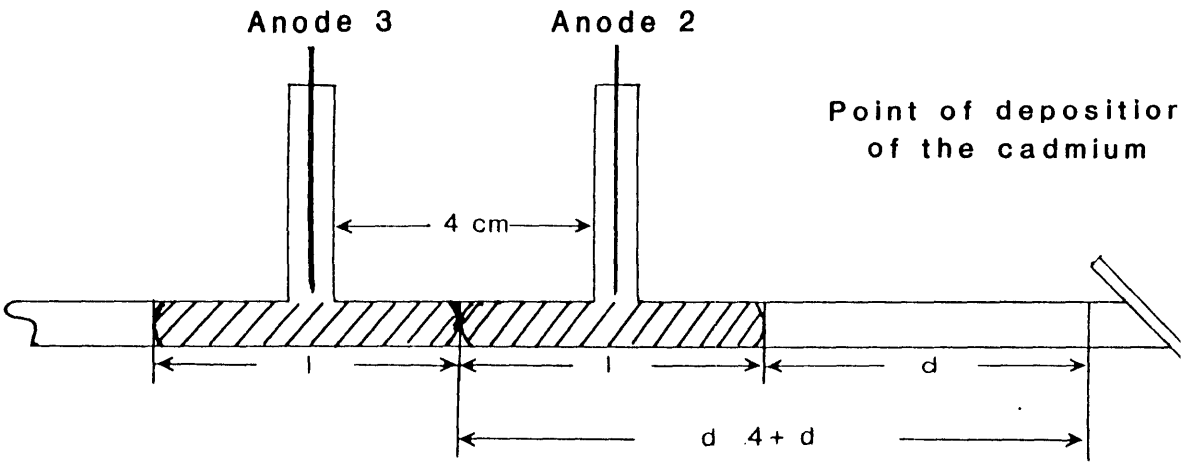

Figure A3.1 Schematic diagram defining the parameters used in the analysis of the cadmium ground state density absorption experiment

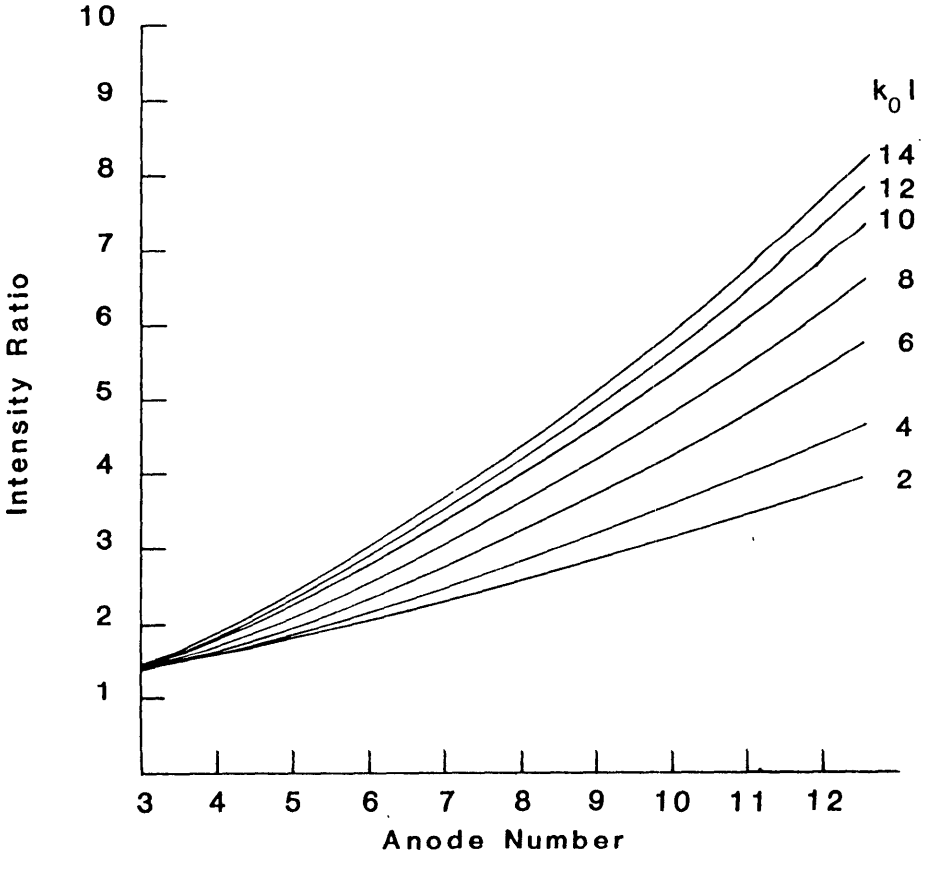

Figure A3.2 3261 Å intensity ratio as a function of anode number and $k_0 l$

TABLE A3.1

Measured and Expected Cadmium Neutral Densities
as a Function of Oven Temperature

OVEN TEMPERATURE ^0C	EXPERIMENT (cm^{-3})	VALUE EXPECTED FROM SVP (cm^{-3})
225	3.6×10^{13}	3.24×10^{13}
250	4.0×10^{13}	1.06×10^{14}
275	5.5×10^{13}	3.09×10^{14}

From Table A3.1 it can be seen that, for an oven temperature of 225°C, the experimental result and the value expected from the saturated vapour pressure data are in good agreement, suggesting that the theory and experimental method are valid. However, for reasons not yet fully understood, there is a large discrepancy between the experimental and theoretical values for oven temperatures greater than 225°C.

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