CHAPTER V

ELECTRON TEMPERATURE DEPENDENCE ON THE TRANSVERSE MAGNETIC FIELD IN A GLOW DISCHARGE IN HELIUM AS OBTAINED FROM SPECTROSCOPIC MEASUREMENTS.

5.1. Introduction

In the previous chapter we have reported measurements of variation of electron temperature with transverse magnetic field of d.c. glow discharges in hydrogen and helium. It was observed there that for relatively small values of reduced magnetic field B/p, electron temperature in a magnetic field B is given by

$$T_{eB} = T_e \left[1 + C_1 \frac{B^2}{p^2} \right]^{1/2} \qquad (5.1)$$

In this chapter x we have reported measurement of variation of electron temperature with transverse magnetic field of a.c. (50 Hz) glow discharge in helium gas. In principle, a 50 Hz a.c. dischage is treated in the same manner as that of a d.c. glow discharge, but from the point of diagnostic, an a.c. glow discharge has the advantage that the radial symmetry of this type of discharge will be less affected in a transverse magnetic field so that two cases e.g. the column deflected towards the collimator or away from the collimator do not arise. The lines selected for determining electron temperature with and without magnetic field by spectral intensity ratio method are the triplet line 4471.5 Å ($1s4d\,^3D \rightarrow 1s2p\,^3P^\circ$) and the singlet line 6678 Å ($1s3d\,^1D \rightarrow 1s2p\,^1P^\circ$). The selected lines have been shown in energy level diagram fig. 4.1.

5.2. Method of measurement

It has been observed that the dependence of electron energy on the cross section for excitation by electron impact differs for the singlet and triplet lines of neutral helium, so the singlet/triplet intensity ratio is a function of electron temperature in a teneous helium plasma. It was first proposed by Cunningham (1955, USAEC Report Wash 289) to use this ratio to determine electron temperature of helium plasma. Since then, the method has been utilised in a large number of works. For two metastable levels 2^3S and 2^1S of helium, generally the population density of 2^1S level is less than that of 2^3S level as 2^1S levels are quickly converted to 2^3S levels by three body collisions. So it is stated that populations of triplet levels of helium in a well contained plasma are influenced by electron impact excitation of the metastable 2^3S level to other triplet levels. Mewe (1966) has deduced a criterion

$$n_e << (10^{12} - 10^{13})\, d^{-1} \quad cm.^{-3} \qquad (5.2)$$

which is to be satisfied for well contained helium plasma of dimension d cm., so that the population of triplet levels are not influenced by 2^3S metastable level population. For a constricted discharge d (= radius of the tube = 0.25 cm.) is small and hence R. Mewe's criterion is well satisfied along with the other criteria as in Table 4.1. When equation (5.2) is satisfied, the metastable atoms diffuse out to the wall of the discharge tube and the triplet level populations are determined from balance between excitation by electron impact of the ground state atoms and spontaneous radiative decay as in SC equilibrium condition.

One of the difficulty that is encountered while determining electron impact excitation rate coefficient X_{1j}, appropriate for as SC model, is that for low energy electrons, the theoretical treatment of electron impact excitation cross sections becomes questionable. In this low energy region, the Born approximation and the convenient sum rules associated with it break down and these have been the primary basis for most theoretical calculations involving impact cross sections. So, what is needed is a systematic method that is capable of representing experimentally known cross sections, or which might permit us to use optical data or other information to infer unmeasured cross sections. The various systematic approaches from a classical or a quantum mechanical basis use rather varied mathematical formalisms. Nevertheless, each approach has been subjected to some phenomenological adjustment, and hence all of them embody experimental information to varying degrees. The approaches have been compared in several reviews (e.g. Green (1966)).

Since the radiationschosen for our experiment have no allowed transition toward the ground level ($1S^2 1S$) the transitions ($1S^2 1S \rightarrow 1S4d^3D$) and ($1S^2 1S \longrightarrow 1S3d^1D$), which enter into the particle balance equation in SC model, are known as optically forbidden transitions. Variens (1969) has discussed the limitations of binary or classical impact theories for optically forbidden transitions. One of the methods, as suggested by A.E.S. Green, is to select the absorption oscillator strength of a companion allowed transition and then treat the transition as an optically allowed transition, may lead to erroneous result for an arbitrary choice of oscillator strength. Such methods needed comparison with experimental

data and the necessary correction. Allen (1963) has described a semiempirical cross section for optically forbidden transition ($1 \rightarrow j$)
as

$$Q_{1j} = \pi a_0^2 \Omega(E) / g_1 E \qquad (5.3)$$

where a_0 is the Bohr radius, g_1 is the statistical weight of ground level and Ω (E) is the dimensionless collision strength which varies from zero at the threshold to a constant value of order unity at one Rydberg for atoms and remaining constant above this energy. For a Maxwellian electron energy distribution the excitation rate coefficient is given by

$$X_{1j} = \left(\frac{8}{m\pi}\right)^{1/2} (kT_e)^{-3/2} \int_{E_j}^{\infty} Q_{1j}(E) E \exp\left(-\frac{E}{kT_e}\right) dE \qquad (5.4)$$

where m , kT_e are the mass and energy in eV of electrons and E_j is the threshold energy for the transition ($1 \rightarrow j$). For low energy electron collision, Benson and Kulander (1972) suggested that Ω (E) may be considered constant with electron energies (within a Maxwellian distribution) if the electron energy exceeds one Rydberg and the constant value is equal to E_H/E_o, where E_H = 13.6 eV and $E_o = E_j$ is the transition energy of the level in eV. So

So from equation (5.3) and (5.4)

$$X_{1j} = \frac{4 E_H \pi a_0^2}{g_1 E_j} \left[\frac{kTe}{2\pi m}\right]^{1/2} \left[\exp\left(-\frac{E_j}{kTe}\right)\right]\left[1-\exp\left(-\frac{E_H}{kTe}\right)\right] \qquad (5.5)$$

Excitation rate coefficient calculated from equation (5.5) compares well with experimental results. From the calculations of Benson and Kulander it appears that for T_e = 25,000°K the ratio $X_{1j} / X_{1\ell}$ for the two lines 6678 Å and 4471.5 Å, calculated from equation (5.5) is 1.31 whereas the experimentally determined value for $X_{1j} / X_{1\ell}$ is 2.73 (St.John et al, 1964). But M.J.Seatons' cross-section with arbitrarily chosen absorption oscillator strengths gives $X_{1j} / X_{1\ell}$ as 13.5. So $X_{1j} / X_{1\ell}$ calculated from equation (5.5) agrees well with experimental data and it is the ratio $X_{1j} / X_{1\ell}$ which enters into relative line intensity ratio.

For optically thin plasma, for two radiations $(j \rightarrow i,\ \ell \rightarrow k)$, the ratio of the intensities is

$$\frac{I_{ji}}{I_{\ell k}} = \frac{\lambda_{\ell k}}{\lambda_{ji}} \frac{X_{1j}}{X_{1\ell}} \frac{A_{ji}}{A_{\ell k}} \frac{\sum A_{\ell m}}{\sum A_{jm}} \qquad (5.6)$$

For equation (5.6) and (5.5) we get

$$kTe = (E_\ell - E_j) \Big/ \ln\left(\frac{I_{ji}}{I_{\ell k}} \frac{E_j}{E_\ell} \frac{\lambda_{ji}}{\lambda_{\ell k}}\right) \qquad (5.7)$$

For radiations chosen

$$A_{ji} / \sum A_{jm} = A_{lk} / \sum A_{lm} = 1 \tag{5.8}$$

When a magnetic field is present

$$\frac{1}{kT_e} - \frac{1}{kT_{eB}} = \ln\left[\frac{(I_{lk})_B}{I_{lk}} \; \frac{I_{ji}}{(I_{ji})_B}\right] / (E_l - E_j) \tag{5.9}$$

So from equation (5.7) and (5.9) electron temperatures without and with transverse magnetic field may be determined. The intensities of line needs correction for dx differential response of the photomultiplier in determining temperature from equation (5.7), but when equation (5.9) is used to determine kT_{eB}, the correction is not needed.

5.3. Experimental arrangement

Experiments were performed on a helium glow discharge at a pressure of one torr. The discharge tube was connected to 50 Hz mains supply through the secondary of a step up transformer. Power to the step up transformer was fed to its primary coil through an auto-transformer. The discharge tube was held vertically and parallel to the collimator slit and was placed in between the pole-pieces of the electromagnet. The magnetic field was varied between 0 - 1200 G. T_e and T_{eB} were determined from the ratio of the intensities of spectral lines 4471.5 Å and 6678 Å. An accurately calibrated spectrograph was used to measure the wavelength of the spectral lines. Each line was focussed on the cathode of the photomultiplier tube $M10FS29V_\lambda$ and the intensities were obtained by measuring the output of photomultiplier tube (details in chapter II). The intensities were corrected for the spectral response of the photomultiplier tube (5% and 8% respectively). The recorded output of the difference amplifier was found to be linearly proportional to known spectral intensities (Internatial critical Table, 1929, Vol. 5), McGraw Hill Book Co.). It is to be noted that T_e and T_{eB} depend upon spectral intensities. To reduce possible error in the recording system, the width of the entrance slit was so adjusted to obtain a large deflection in the output microammeter of the difference amplifier, thereby increasing the sensitivity in the measurement of line intensity ratio.

5.4. Results and discussions

The energy of the upper levels of the radiations chose are after Moore (1971).

4471.5 Å ($l \rightarrow k$), E_l = 23.736 eV.

6678.2 Å ($j \rightarrow i$), E_j = 23.073 eV.

value of kT_e obtained is 1.78 eV. Variation of electron temperature with transverse magnetic field has been shown in Table 5.1.

TABLE 5.1.

(Variation of electron temperature of a.c. helium glow discharge with transverse magnetic field).

Magnetic field (G)	$\frac{(I_{4771.5})_B}{I_{4771.5}} = x$	$\frac{(I_{6678})_B}{I_{6678}} = y$	$\frac{\ln(x/y)}{E_i - E_j}$	kT_e (eV)
0	1	1	0	1.78
240	1.06383	1.05532	1.2113 x 10^{-2}	1.82
390	1.12765	1.10212	3.454 x 10^{-2}	1.90
550	1.18085	1.12765	6.953 x 10^{-2}	2.03
650	1.21702	1.14893	8.6835 x 10^{-2}	2.11
750	1.2468	1.17021	9.562 x 10^{-2}	2.15
1000	1.38297	1.27659	1.2072 x 10^{-1}	2.27

Values of $[(T_{eB}/T_e)^2-1]$ versas B^2/p^2 have been entered into Table 5.2.

TABLE 5.2

Values of $[(T_{eB}/T_e)^2-1]$ Vs B^2/p^2.

B^2/p^2 $\times 10^{-5}$ $G^2/torr^2$	0	0.576	1.521	3.025	4.225	5.625	10
$\left(\frac{T_{eB}}{T_e}\right)^2-1$	0	0.0454	0.1394	0.3006	0.4052	0.4589	0.6263

In fig. (5.1), $[(T_{eB}/T_e)^2-1]$ has been plotted against B^2/p^2 and from the fig. it is observed that equation (5.1) as deduced by Sen et al (1972) is valid for electron temperatures for values of reduced magnetic field $B/p \leq 670$ G/torr. For $B/p > 670$ G/torr the deduction is not valid which is due to the fact that in deducing equation (5.1) from L. Beckman's equation it was assumed that the reduced magnetic field B/p is small

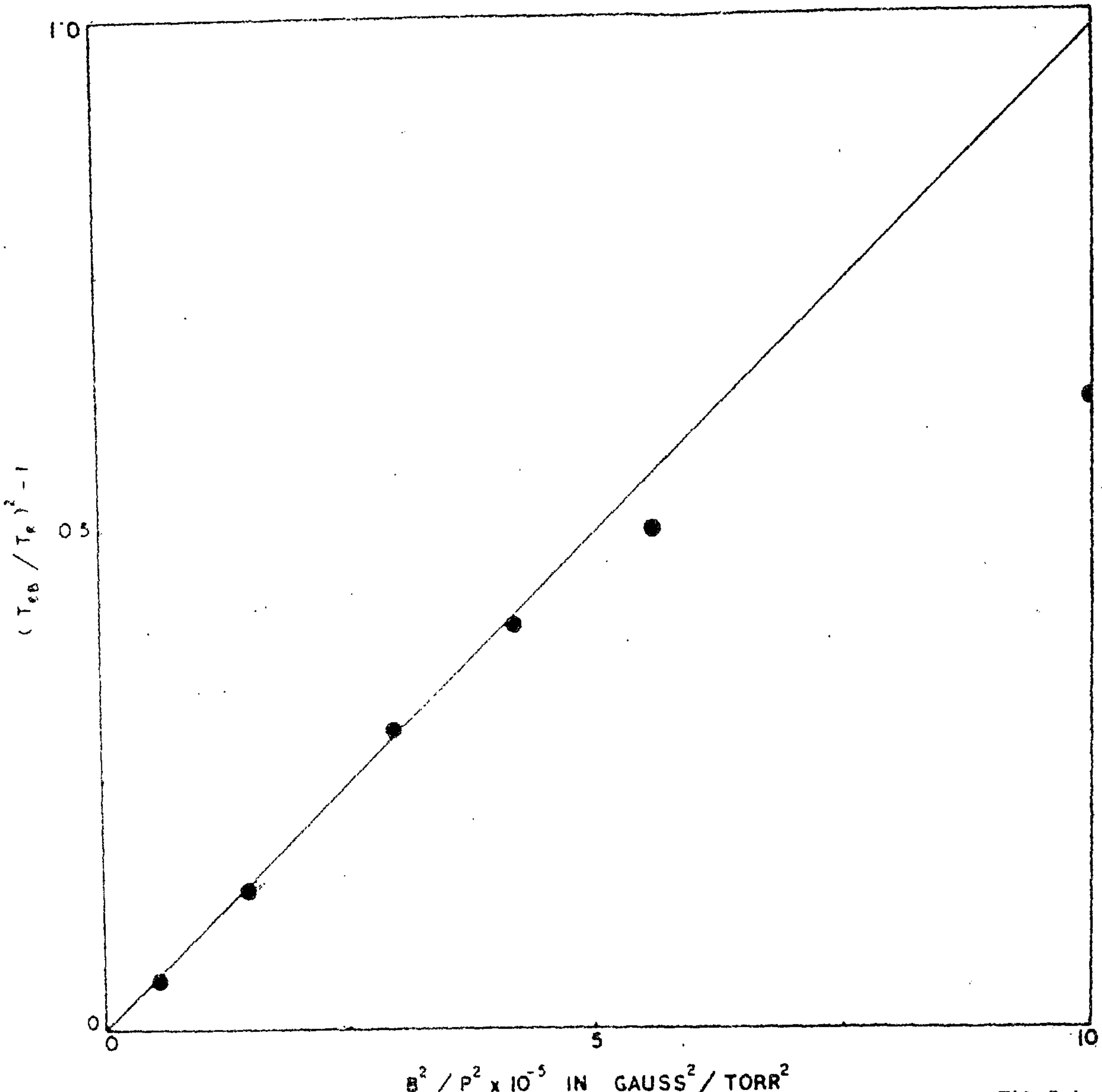

Fig. 5.1. Variation of $(T_{eB}/T_e)^2 - 1$ with B^2/p^2 for helium in transverse magnetic field (SC model).

Value of C_1 calculated from the slope is 0.99×10^{-6}. C_1 is the value of square of the electron mobility at a pressure of 1 torr at 0°C. So electron mobility at 1 torr pressure may be calculated as 10^{-3} torr/G or 10 torr/kg(amp. sec.^{2})$^{-1}$. (The conversion is 10^4 gauss = 1 kg/amp. sec.^{2}). For a comparison of this value of mobility with other literature values, the value of E/N or E/p is needed. Value of E/N could not be determined experimentally. But from the value of electron temperature i.e. D/μ , value of E/N is found from the table of Huxley and Crompton (1974) as E/N > 3 Td. . (E/N (TD) = 3.03 E/p). Considering E/p 10 V cm^{-1} $torr^{-1}$ or E/p = 10^3 V m^{-1} $torr^{-1}$, value of drift velocity of electrons in helium at a pressure of 1 torr is calculated from the value of mobility from C_1, as 10^4 m. $sec.^{-1}$. This value compares well with value given by Franklin (1976) 6×10^4 m. $sec.^{-1}$.

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ELECTRON TEMPERATURE DEPENDENCE ON THE TRANSVERSE MAGNETIC FIELD IN A GLOW DISCHARGE AS OBTAINED FROM SPECTROSCOPIC MEASUREMENTS

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The electron temperature of a helium plasma has been measured spectroscopically as a function of the magnetic field. For lower values of the magnetic field, the variation of T_e with the field can be represented by an expression deduced by Sen and Gupta.

It has been shown by several authors [1–4] that the electron temperature T_e and the axial electric field of a steady uniform positive column in a low pressure d.c. discharge change in the presence of a transverse magnetic field. When such a magnetic field is present, the electrons and ions drift across the magnetic lines of force in cycloidal motion between collisions. The flow of ions and electrons in the direction of the lorentzian force causes a deflection of the current and cylindrical symmetry of the discharge towards the wall, causing a corresponding increase in the axial electric field and electron temperature. For relatively small values of the reduced field B/P, where B is the transverse magnetic field in Gauss and P the pressure in Torr, Sen et al. [2] have shown

$$T_{eB} = T_e[1 + C_1 B^2/P^2]^{1/2} , \qquad (1)$$

where $C_1 = ((e/m)L/v_r)^2$, L being the mean free path of the electron at a pressure of 1 Torr and v_r the random velocity of the electron and e and m are the charge and mass of the electron, respectively.

We have investigated the variation of T_e with the applied transverse magnetic field for an a.c. (50 Hz) low pressure helium discharge and have checked the validity of eq. (1) for such plasmas. T_e was determined spectroscopically by measuring the intensity of the $\lambda = 4471.5$ Å ($2^3P \rightarrow 4^3D$) and $\lambda = 6678$ Å ($2^1P \rightarrow 3^1D$) lines. Since the electron density n_e for such low pressure, low power glow discharges is much less than the value of n_e required for the establishment of LTE or partial LTE [5] we have assumed a semicoronal equilibrium to prevail inside the discharge tube [6]. In this model the atoms are excited by electron impact to the states concerned directly from the ground state. Since the levels chosen have no optically allowed transition to the ground level of He, the cross section of excitation by electron impact for optically forbidden transitions is to be considered. Limitations of binary or classical encounter theories for such cross sections have been discussed by Viens [7]. Allen [8] has described a semiempirical cross section for such transitions as

$$\sigma = \pi a_0^2 \Omega(E)/g_1 E , \qquad (2)$$

where $\Omega(E)$ is the dimensionless collision strength which varies from 0 at threshold to a constant value R of the order of unity at 1 Ry remaining constant above this energy. E is the electron energy in Ry, g_1 is the statistical weight of the ground level and a_0 the Bohr radius. Since for He glow discharges the electron energy distribution function may be approximated to be maxwellian [9] taking $R = E_H/E_0$ [10], where $E_H = 13.6$ eV and E_0 the transition energy of the level in eV, the rate of excitation from the ground level to a level (k) is

$$n_e n_1 \langle \sigma v_e \rangle = n_e n_1 \frac{4E_H \pi a_0^2}{g_1 E_0} \left[\frac{kT_e}{2\pi m}\right]^{1/2} \times \left[\exp\left(-\frac{E_0}{kT_e}\right)\right] \left[1 - \exp\left(-\frac{E_H}{kT_e}\right)\right] . \qquad (3)$$

Considering the plasma to be optically thin and uniform, the intensity of a line $k \to i$ is given as

$$I_{ki} = \frac{hl\nu_{ki}}{4\pi} n_e n_1 \langle \sigma v_e \rangle A_{ki} \Big/ \sum_{m<k} A_{km} \,. \qquad (4)$$

Taking the intensity ratio of two lines $l \to j$ and $k \to i$ we get

$$kT_e = (E_l - E_k) \Big/ \ln\left(\frac{I_{ki}}{I_{lj}} \frac{E_k}{E_l} \frac{\lambda_{ki}}{\lambda_{lj}}\right), \qquad (5)$$

where the E's and λ's are the energy of the levels and the wavelength of the radiations. For the radiations chosen

$$A_{ki} \Big/ \sum_{m<k} A_{km} = 1.$$

When a magnetic field is present

$$\frac{1}{kT_e} - \frac{1}{kT_{eB}} = \ln\left[\frac{(I_{lj})_B}{I_{lj}} \frac{I_{ki}}{(I_{ki})_B}\right] \Big/ (E_l - E_k) \,. \qquad (6)$$

Details of the experimental arrangement are given in a previous paper [3]. Experiments were performed on an a.c. glow discharge of helium at a pressure of 1 Torr. The discharge tube of radius 1 cm, and 15 cm in length, was placed vertically between the poles of an electromagnet and the magnetic field (0–1200 G) was uniform inside the poles. The electron temperature T_e and T_{eB} without and with the transverse magnetic field, respectively, were determined by taking the intensity ratios of the spectral lines 4471.5 Å and 6678 Å, see eqs. (5) and (6). An accurately calibrated constant deviation spectrograph was used to measure the wavelength of the spectral lines. Each line was focussed on the cathode of the photomultiplier tube M10FS29 V_λ and the intensities were obtained by measuring the output of the photomultiplier which was recorded by a difference amplifier. It is to be noted from eq. (5) that an error in the value of T_e can arise only in the measurement of the observed line intensity ratio $[I_{ki}/I_{lj}]$ as all other quantities have standard values. To reduce the possible errors the recording system was calibrated [3]. The intensities of the lines were corrected for the spectral response of the photomultiplier tube. The recorded output of the difference amplifier was found

Table 1

Magnetic field (G)	$\frac{(I_{4471.5})_B}{I_{4471}} \frac{I_{6678}}{(I_{6678})_B}$	kT_e (eV)
0	1	1.78
240	1.0081	1.82
390	1.0232	1.90
550	1.0472	2.03
650	1.0593	2.11
750	1.0654	2.15
1000	1.0833	2.27

to be linearly proportional to the known spectral intensities (International Critical Table, Vol. 4) and the width of the entrance slit was adjusted to obtain a large deflection in the output microammeter of the difference amplifier, thereby increasing the sensitivity in the measurement of the line intensity ratio. The value of T_e obtained here is in close agreement with the experimentally determined value of T_e for helium (Franklin [11]). The accuracy in the measurement of T_{eB} depends upon the experimentally observed ratio of both line intensities when a magnetic field is present. The transverse magnetic field produces some asymmetry and inhomogeneity in the spectral column but since the inhomogeneity will be along the line of sight both lines will be affected by almost the same degree due to this inhomogeneity. The energy values of the levels are tabulated in ref. [12]. Axial spectral intensities were

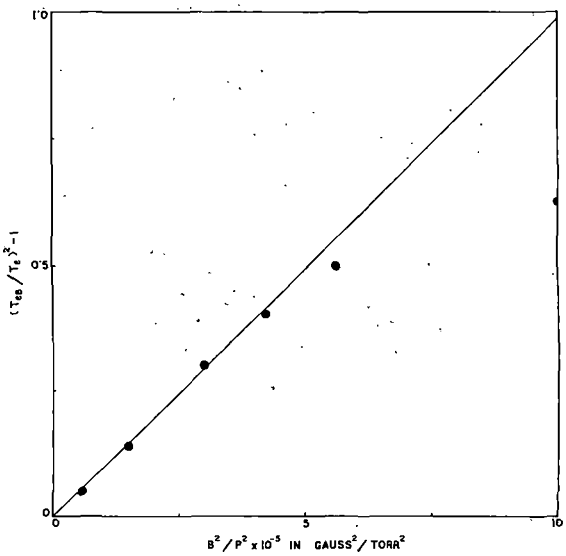

Fig. 1.

found to increase with magnetic field. Table 1 shows T_e values obtained spectroscopically up to 1000 G of magnetic field strength. Fig. 1 is a plot of $[T_{eB}^2/T_e^2 - 1]$ against B^2/P^2 and shows the validity of eq. (1) up to a magnetic field strength of 650 G. The slope of the curve gives a value of $C_1 = 0.99 \times 10^{-6}$.

It is observed that for $B/P > 650$ G/Torr, the deduction is not valid which is due to the fact that in deducing eq. (1) from Beckman's equation it was assumed that B/P is small. The constant $C_1 = ((e/m)/L/v_r)^2$ is the square of the mobility of the electrons in the gas at a pressure of 1 Torr and its numerical value as obtained here is consistent with the data found in the literature [11].

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Mercury arc plasma in an axial magnetic field

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The electron temperature of a mercury arc plasma (arc current 2·25 A and 2·5 A) has been measured spectroscopically in an axial magnetic field varying from zero to 1050 gauss. It has been noted that the electron temperature decreases with the increase of the magnetic field. Considering the physical processes involved in a mercury arc discharge where the buffer gas is air and the pressure low, a model has been developed in which air plays the role of a quenching gas, and it has been found that in this type of discharge both atomic and molecular ions of mercury are present. Assuming the presence of both types of ions a radial distribution function for the electron density has been deduced and an expression for T_e/T_{eB} has been obtained. It has been found that within the range of (B/P) values used here the experimental results are in quantitative agreement with the theoretical deduction. The increase of radial electron density in an axial magnetic field as obtained by the probe method can also be explained by the theory developed.

1. Introduction

It is well known that plasma parameters such as electron density and electron temperature undergo a change when the plasma is subjected to a magnetic field, and in a detailed investigation (Sadhya *et al.* 1979) it has been shown that when the magnetic field is transverse to the direction of flow of the discharge current, the electron temperature increases and the azimuthal electron density decreases, whereas if the magnetic field is longitudinal the reverse effect takes place.

It is worthwhile investigating whether the physical processes undergo any significant change when we pass from the glow to the arc region, and in a previous investigation (Sen and Das 1973) it was established that in the case of a mercury arc plasma (current 1 A to 2·5 A) the electron temperature increases in a transverse magnetic field and that the results are in quantitative agreement with Beckman's theory (1948) as modified by Sen and Gupta (1971), especially for small values of the reduced magnetic field.

The effect of a longitudinal magnetic field on a low pressure mercury arc has been investigated by various workers (Cummings and Tonks 1941, Forest and Franklin 1966 and Vorobjeva *et al.* 1971); but there is shortage of data for high pressure, large current plasma with longitudinal magnetic field.

In the present investigation the variation of current and voltage across a mercury arc plasma as well as variation of the electron temperature are studied in a longitudinal magnetic field. Most of the results reported for mercury arc plasma are with argon as background gas; in the present investigation air is the background gas, which enables us to study how the excitation, ionization and de-ionization processes are influenced by the presence of air.

In the case of molecular gases the ionization is mainly due to electron impact of the ground state atom whereas in the case of a mercury arc, ionization is

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mainly through inelastic electron impact with excited states like 6^3P_2 and with ground states, and the phenomena of associative ionization may also be present. Hence the physical processes occuring in a mercury arc plasma and how these processes are influenced by the magnetic field have to be taken into consideration in deducing the electron temperature and its variation in a magnetic field.

2. Experimental measurements and results

Experiments were performed on a d.c. mercury arc at low pressure, burning in air. The discharge currents were 2·25 A and 2·5 A, while the dry air pressure was varied from 0·05 torr to 2 torr. Electron temperature T_e and T_{eB} without and with magnetic fields were determined by measuring the intensities of $\lambda 5770$ Å ($6^3D_2 \rightarrow 6^1P_1$) and $\lambda 5790$ Å (6^3D_1, $6^1D_1 \rightarrow 6^1P_1$) and taking their ratios. As the radiations differ by only 20 Å they would have equal response in the photomultiplier tube (MIOFS29V_λ) used.

A vertical mercury arc tube 10 cm in length and 1 cm in radius, burning in dry air and cooled externally was mounted in between the pole pieces (diameter 5 cm), and along the lines of force of the electromagnet. The discharge filled the tube totally. An accurately calibrated constant deviation spectrograph was used to measure the wavelength of the spectral lines. Each line was focused on the cathode of the photomultiplier tube operated at 1425 V. Detailed electronic arrangements for measuring the intensity of the spectral lines are given in an earlier paper (Sen, *et al.* 1972). The magnetic field (0–1100 gauss) was uniform inside the pole pieces.

The pressure of air which was introduced through a needle valve, was measured by a McLeod gauge and the pressure of mercury was determined after noting the temperature of the wall by a mercury-in-glass thermometer. In the present investigation we have taken measurements with two types of arc discharges, (*a*) $i = 2{\cdot}25$ A $P_{air} = 0{\cdot}08$ torr, $P_{Hg} = 0{\cdot}3032$ torr, (*b*) $i = 2{\cdot}5$ A. $P_{air} = 0{\cdot}08$ torr and $P_{Hg} = 0{\cdot}3731$ torr. The variation of current and voltage across the arc were noted for both types of discharge and for a wide range of magnetic field varying from 0 to 1100 gauss.

For the measurement of T_e from the intensity of spectral lines it has been shown by Griem (1963) that for LTE (Local Thermal Equilibrium) to be valid the electron density n_e should be greater than 10^{16} cm^{-3}. Since cross-sections increase rapidly with principal quantum numbers whereas radiative decay rates decrease, the highly excited states may be in equilibrium with the continuum, which leads to the idea of partial LTE and the condition for this to be valid has been obtained by Griem (1963) as $n_e \geqslant 10^{12}$ cm^{-3} which is valid in this case.

Hence under this condition

$$KT_e = \frac{(E_j - E_k)}{\ln\left[\frac{I_{ki}}{I_{ji}}\frac{A_{ji}}{A_{ki}}\frac{\lambda_{ki}}{\lambda_{ji}}\frac{g_j}{g_k}\right]} \tag{1}$$

where I_{ki} and I_{ji} are the intensities of spectral lines for the transitions $k \rightarrow i$ and $j \rightarrow i$ respectively and other symbols have their usual significance. The values of A_{ji} and A_{ki} have been taken from Mosberg and Wilkie (1978).

As the spectrograph used is unable to resolve the Zeeman splitting of the line in the magnetic field and the spectral intensity of the lines changes in the magnetic field (Sen *et al.* 1972) it can be deduced from eqn. (1) that

$$\frac{1}{KT_{eB}}-\frac{1}{KT_e}=\frac{\ln\left[\frac{(I_{ki})_B}{I_{ki}}\Big/\frac{(I_{ji})_B}{I_{ji}}\right]}{(E_j-E_k)} \tag{2}$$

where $(I_{ki})_B$ and $(I_{ji})_B$ are the intensities of the lines in the presence of the magnetic field and T_{eB} is the electron temperature in the magnetic field. The results for the measurement of intensities of the lines with and without magnetic field and the corresponding electron temperature are shown in Tables 1 and 2.

Magnetic field in gauss.	$\frac{(I_{5790})_B}{I_{5790}}=A$	$\frac{(I_{5770})_B}{I_{5770}}=B$	$\ln\frac{A}{B}$	T_e(eV)
0	1	1	0	0·412
255	1·02586	1·01852	$7·1806\times10^{-3}$	0·313
550	1·08621	1·07407	$1·1239\times10^{-2}$	0·282
835	1·14655	1·12963	$1·4867\times10^{-2}$	0·256
1050	1·17241	1·15278	$1·6887\times10^{-2}$	0·243

Table 1. $i=2·5$ A, $P_{Hg}=0·3731$ torr, $P_{air}=0·08$ torr.

Magnetic field in gauss.	$\frac{(I_{5790})_B}{I_{5790}}=A$	$\frac{(I_{5770})_B}{I_{5770}}=B$	$\ln\frac{A}{B}$	T_e(eV)
0	1	1	0	0·412
255	1·02913	1·02	$8·9072\times10^{-3}$	0·301
550	1·07282	1·06	$1·2017\times10^{-2}$	0·276
835	1·13592	1·12	$1·4116\times10^{-2}$	0·261
1050	1·19417	1·175	$1·6187\times10^{-2}$	0·247

Table 2. $i=2·25$ A, $P_{Hg}=0·3022$ torr, $P_{air}=0·08$ torr.

3. Discussion of results

It is noted that when the magnetic field is applied the discharge current decreases, and since the supply voltage to the arc is constant the voltage across the discharge tube will increase.

To get the value of n_e, the electron density, we note that

$$i=\mu Ee2\pi\int_0^R n_r r\,dr$$

where n_r is the radial electron density and μE is the drift velocity of electrons for the mercury and air mixture. For this type of discharge no data for μE are available so values for electrons in mercury vapour are taken from the paper of Nakamura and Lucas (1978) where $P_{Hg}\gg P_{air}$ as in this case.

Considering the distribution to be besselain

$$i = \mu E e 2\pi n_{eo} \frac{R^2}{2{\cdot}405} J_1(2{\cdot}405)$$

From the above equation we get the value of $\bar{n}_e$ the electron density averaged radially ($\bar{n}_e = 0{\cdot}432 n_{eo}$) ; when $i = 2{\cdot}5$ A, $\bar{n}_e = 1{\cdot}645 \times 10^{13}$ cm^{-3} and for $i = 2{\cdot}25$ A $\bar{n}_e = 5{\cdot}687 \times 10^{12}$ cm^{-3}. This result indicates that for the mercury arc discharge used here partial LTE is valid and eqns. (1) and (2) can be used for the measurement of T_e and T_{eB} respectively.

Further

$$i = e^2 E \frac{D_e}{KT_e} 2\pi \int_0^R n_r r \, dr \tag{3}$$

and

$$i_B = e^2 E_B \frac{D_{eB}}{KT_{eB}} 2\pi \int_0^R n_{rB} r \, dr \tag{4}$$

where D_e is the diffusion coefficient of electrons and the subscript B denotes quantities in the magnetic field. To get an expression for the electron density distribution we have to consider the model of a mercury arc burning in air at low pressure.

The discharge is axially homogeneous and cylindrically symmetric. The concentration of mercury ground-state atoms is taken to be constant across the cross-section of the tube and is determined by the temperature of the wall. Only the mercury atoms are excited and ionized by electron impact. No line emission from air (i.e. N_2 or O_2) was observed. The concentration of the buffer gas which is dry air is also uniform across the tube cross-section and it plays a role in ambi-polar diffusion and mobilities of charged particles and in de-activating excited mercury atoms. We disregard the depletion of mercury ground-state atoms density at the axis of the discharge tube which is generally observed in low gas temperature experiments.

It is assumed that (i) the principal excited species are 6^3P_2 6^3P_1 and 6^3P_0 with densities n_2, n_1 and n_0 respectively and that cascading to these levels is not important in maintaining the densities, (ii) the diffusion losses can be accounted for by introducing a diffusion length, and (iii) the presence of a buffer gas like air will result in de-activation or quenching of excited species. It is assumed here that energy differences are given to molecular gases as vibrational energies.

Air constituents, chiefly nitrogen and oxygen are found to be good de-activating agents. The chief de-activating processes are

I $6^3P_0 + O_2 \rightarrow 6^1S + O_2^*$

II. $6^2P_1 + N_2 \rightarrow 6^3P_0 + N_2^*$

III $6^3P_1 + N_2 \rightarrow 6^1S + N_2^*$

IV $6^3P_1 + O_2 \rightarrow 6^1S + O_2^*$

V de-activation of 6^3P_0 atoms by Hg ground-state atoms should be considered.

The cross-sections of the processes are given in Messay *et al.*, (1971)

$$\sigma_I = 0{\cdot}31 \times 10^{-16} \text{ cm}^2, \quad \sigma_{II} = 1{\cdot}3 \times 10^{-16} \text{ cm}^2$$

$$\sigma_{III} = 3 \times 10^{-16} \text{ cm}^2, \quad \sigma_{IV} = 4{\cdot}4 \times 10^{-16} \text{ cm}^2$$

$$\sigma_V = 23{\cdot}9 \times 10^{-16} \text{ cm}^2$$

Including these processes in the equation of Forrest and Franklin (1969) we get

$$-d_0n_0+En_en_g+Wn_en_1+Gn_1n_g-(U+C+S)n_en_0-Hn_en_0 \\ -Bn_0n_2-Zn_gn_0-Yn_0n_{O_2}+X_1n_1n_{N_2}=0 \quad (5)$$

$$-d_0n_2+Fn_en_g+Jn_en_1-Kn_2n_g-(R+D+T)n_en_2-Bn_0n_2=0 \quad (6)$$

$$-d_0n_1+Ln_en_g-n_1/\tau+Mn_gn_p-(N+J+W)n_1n_e+Gn_1n_g+Tn_en_2 \\ +Un_0n_e-Hn_0n_1+Kn_2n_g-Xn_1n_{N_2}-Vn_1n_{O_2}=0 \quad (7)$$

$$-d_pn_1-Mn_gn_p+n_1/\tau=0 \quad (7')$$

where

Y is related to process I
X_1 is related to process II
X is related to process II+III
V is related to process IV
Z is related to process V

and other symbols have their significance as in Forrest and Franklin (1969) and n_{O_2} and n_{N_2} are the number densities of oxygen and nitrogen molecules.

To calculate the densities we note that for the 6^1S_0 state atom densities are as follows

$$\text{at } T_\omega=96°\text{C}, \quad P_{Hg}=0{\cdot}3032 \text{ torr}, \quad n_g=7{\cdot}83\times10^{15}\text{ cm}^{-3}$$

$$\text{at } T_\omega=106°\text{C}, \quad P_{Hg}=0{\cdot}3731 \text{ torr}, \quad n_g=1{\cdot}3282\times10^{16}\text{ cm}^{-3}$$

and evidently $n_g>n_2$, n_1, n_0 or n_e.

To get the values of n_0, n_1 and n_2 as a first approximation we can neglect the terms Jn_en_1 and Bn_0n_2 in eqn. (6) as $n_g\gg n_2$, n_1, n_0, n_e which leaves us with an equation containing n_2, and values of n_g and n_e are known.

The values of different coefficients can be evaluated by assuming the electron energy distribution to be maxwellian and assuming the expression given by Sampson (1969) for the optically allowed transition for electron impact ionization as

$$\langle v_e\sigma\rangle=\pi a_0^2\left(\frac{8KT_e}{m\pi}\right)^{1/2}\left[4f_{ig}\left(\frac{E_H}{E_0}\right)^2\right]\frac{2\pi}{\sqrt{3}}\frac{E_0}{KT_e}\exp\left(-\frac{E_0}{KT_e}\right)P\left(\frac{E_0}{KT_e}\right)$$

where $\pi a_0^2=8{\cdot}797\times10^{-17}$ cm^2, E_0 is the threshold energy of the transition, and f_{ig} the oscillator strength for the ($6^1S_0\rightarrow6^3P_1$) transition, values of which have been given by Sampson (1969).

For optically forbidden transitions we have taken the expression of Benson and Kulandar (1972) which utilized Allen's cross section as

$$\langle v_e\sigma\rangle=\frac{4E_H\pi a_0^2}{g_eE_0}\left(\frac{KT_e}{2\pi m}\right)^{1/2}\exp\left(-\frac{E_0}{KT_e}\right)\left\{1-\exp\left(-\frac{E_H}{KT_e}\right)\right\}$$

where g_e is the statistical weight of the state from which excitation is considered.

For the atom–atom/molecule reaction

$$\langle v\sigma\rangle=\sigma\left(\frac{8KT_g}{\mu\pi}\right)^{1/2}$$

where σ is the effective cross-section for the process considered and μ is the reduced mass of the colliding atoms and molecules.

Having determined the value of n_2, n_1 can be found from eqn. (7) and putting this value of n_1 in eqn. (5) n_0 can be obtained. Taking these values of n_0, n_1, and n_2 the equations are evaluated afresh by considering all the terms of the three equations. This procedure is repeated and the change in the values of the n's is found to be small. Results of calculation of species densities are entered in Table 3. To bring out the influence of buffer gas pressure, calculations are given for $P_{air} = 0{\cdot}05$ torr and $P_{air} = 2$ torr.

Condition of plasma	i	2·5 A	2 A
	P_{air}	0·05 torr	2 torr
	P_{Hg}	0·3771 torr	0·222 torr
	T_e	0·5 eV	0·5 eV
Number of densities in $cm^{-3} \times 10^{-10}$	n_{N2}	$1{\cdot}424 \times 10^5$	$5{\cdot}664 \times 10^6$
	n_{O2}	$3{\cdot}56 \times 10^4$	$1{\cdot}424 \times 10^6$
	n_g	$1{\cdot}328 \times 10^6$	$7{\cdot}83 \times 10^5$
	n_0	68·6	7·788
	n_1	19·13	1·423
	n_2	86·2	42·7
	n_e	$1{\cdot}64 \times 10^3$	$5{\cdot}687 \times 10^2$

Table 3.

Now let us look into the ionization process in these types of discharges. The chief ionization processes in a mercury discharge are listed in Vriens *et al.* (1978).

1. $Hg(6^1S_0) + e \rightarrow Hg^+ + 2e$
2. $Hg(6^3P_0) + e \rightarrow Hg^+ + 2e$
3. $Hg(6^3P_1) + e \rightarrow Hg^+ + 2e$
4. $Hg(6^3P_2) + e \rightarrow Hg^+ + 2e$
5. $Hg(6^3P_0) + Hg(6^3P_2) \rightarrow Hg_2^+(6^2\Sigma^+) + e$

6 (*a*). $Hg(6^3P_1) + Hg(6^3P_2) \rightarrow Hg^* + Hg(6^1S_0)$

6 (*b*). $Hg^* + e \rightarrow Hg^+ + 2e$

another process namely

7. $Hg(6^3P_2) + Hg(6^3P_2) \rightarrow Hg^+(6^2S_{1/2}) + Hg(6^1S_0) + e$

is not considered by us as spin is not conserved. Electron impact ionization rates from different levels $K_1 \rightarrow K_4$ for processes 1 to 4 are given by Sampson (1969)

$$n_e n_i \langle \sigma_e v \rangle = 5{\cdot}465 \times 10^{-11} n_e n_i T_e^{1/2} \exp\left(-\frac{eX_i}{KT_e}\right) \Gamma_i(T_e) \qquad (8)$$

$$i = g,\ 0,\ 1,\ 2.$$

here T_e is the electron temperature in K, eX_i is the ionization energy of the ith level and $\Gamma_i = An/X_i^2$ where $A = 200$ for neutral atoms, and n = number of electrons per atom in the outer orbit. For process 5, the rate is

$$K_5 = n_0 n_1 \langle \sigma_5 v \rangle \qquad (9)$$

$$= n_0 n_1 \sigma_5 \langle v \rangle$$

σ_5 is the effective cross-section for associative ionization. Tan and Von Engel (1968) have determined

$$\sigma_5 = 46 \times 10^{-15}\ \mathrm{cm}^2 \quad \text{and} \quad \langle v \rangle = \left(\frac{16KT_g}{\pi m}\right)^{1/2}$$

For process 6

$$K_6 = n_1 n_2 \sigma_6 \langle v \rangle B_i \tag{10}$$

σ_6 is estimated by Vriens *et al.* (1978) to have a value of $10 \times 10^{-15}\ \mathrm{cm}^2$, B_i is the branching ratio and as calculated by the authors, B_i should be slightly less than unity.

All the atoms in the highly excited states populated by process 6(*a*), are ionized by electron impact, very few of them will make optically allowed transitions. We have neglected ionization from the 6^1P_1 level since the population density and natural life time of this level are small. With the help of eqn. (8), (9) and (10) and utilizing the values of n_e, n_g, n_0, n_1, and n_2 (Table 3) the rates of ionization for the two types of discharges considered here have been calculated and are entered in Table 4.

Discharge conditions	i	2·5 A	2 A
	T_e	0·5 eV	0·5 eV
	P_{air}	0·05 torr	2 torr
	P_{Hg}	0·3731 torr	0·222 torr
Rate of ionization in $s^{-1} \times 10^{-11}$	K_1	11·585	5·41
	K_2	21·94	1·98
	K_3	10·13	0·61
	K_4	181·37	71·2
	K_5	1700	8·72
	K_6	466·4	16·94

Table 4.

From Table 4 it is evident that for a plasma where air pressure is comparatively small, ionization is chiefly through the process of associative ionization and by electron impact ionization of highly excited Hg atoms whereas when P_{air} is comparatively large due to large quenching of 6^3P_0 levels ionization will be primarily through the process of electron impact of 6^3P_2 atoms. So in type I plasma where P_{air} is small two types of ions Hg_2^+ and Hg^+ prevail inside the discharge tube. To calculate the normal distribution in a mercury discharge with two types of ions, we can utilize the equations of Golubovskii and Lyaguschenko (1977)

$$\left.\begin{aligned} \operatorname{div} \mathbf{J}_{i1} &= -D_{a1}\nabla\left(\frac{n_{i1}}{n_e}\nabla n_e\right) = F_1 \\ \operatorname{div} \mathbf{J}_{i2} &= -D_{a2}\nabla\left(\frac{n_{i2}}{n_e}\nabla n_e\right) = F_2 \\ F_1 + F_2 &= F_e \end{aligned}\right\} \tag{11}$$

and

where n_{i1} and n_{i2} are the number densities of Hg^+ and Hg_2^+ ions, $\mathbf{J}_{i1}$ and $\mathbf{J}_{i2}$ are the current densities, n_e is the electron density, $D_{a12} = D_e(\mu_{i12}/\mu_e)$. F_1, F_2 and F_e are the differences between the rates at which particles appear and disappear in the volume, μ is the mobility.

Kovar (1964) has shown that actually $\mu_{i2}/\mu_{i1} = 1{\cdot}875$. It may be interesting to note that heavier ions are faster. The reason behind this is that atomic ions moving in their parent gas will have large charge exchange cross-section and hence progress more slowly than the heavier molecular ions which do not suffer resonance charge exchange collisions. As the difference in μ values is small and the presence of foreign gas will effectively reduce the charge exchange phenomena and obscure the vision of Hg^+ ions for resonance to occur, the atomic and molecular ionic mobilities may be assumed equal.

Atomic ions will be produced mainly by (i) electron impact of highly excited states of Hg atoms at rate $\nu_i n_e$ and these states are in thermal equilibrium with the electrons, (ii) by electron impact dissociation of molecular ions with a rate $\omega n_{i2} n_e$ and they will be lost mainly by

(i) ambi-polar diffusion to the wall,
(ii) conversion to molecular ions in three-body collisions at rate $\kappa n_{i1} n_e$

Hence

$$F_1 = \nu_i n_e + \omega n_{i2} n_e - \kappa n_{i1} n_e \tag{12}$$

Molecular ions will be produced mainly by

(i) the process of associative ionization with rate g.
(ii) conversion of atomic ions at a rate $\kappa n_{i1} n_e$

and they will disappear by

(i) ambi–polar diffusion
(ii) electron impact dissociation to atomic ions at a rate $\omega n_{i2} n_e$.

We have neglected dissociative recombination of molecular ions. Hence

$$F_2 = g + \kappa n_{i1} n_e - \omega n_{i2} n_e \tag{13}$$

Hence from eqns. (11), (12) and (13) we get

$$\nu_i n_e + g = -D_a \nabla^2 n_e \quad \text{as } n_{i1} + n_{i2} = n_e \tag{14}$$

we have neglected any variation of excited state density across the tube cross section. In cylindrical co-ordinates system eqn. (14) reduces to

$$D_a \frac{1}{r}\frac{d}{dr}\left(r\frac{dn_r}{dr}\right) + g + \nu_i n_r = 0 \tag{15}$$

The solution of the equation is

$$n_r = \frac{n_{eo}}{1 - J_0\left(R\sqrt{\frac{\nu_i}{D_a}}\right)}\left\{J_0\left(r\sqrt{\frac{\nu_i}{D_a}}\right) - J_0\left(R\sqrt{\frac{\nu_i}{D_a}}\right)\right\} \tag{16}$$

where n_{eo}, the electron density at the axis is

$$\left.\begin{aligned} n_{eo} &= \frac{g}{\nu_i J_0 \sqrt{\alpha}}\,[1 - J_0\sqrt{\alpha}] \\ \text{and} \qquad \alpha &= R^2 \nu_i / D_a \end{aligned}\right\} \tag{17}$$

(A standard derivation of eqn. (15) can be found in the Appendix).

It is evident from eqn. (16) that the normal distribution in presence of the magnetic field will be given by

$$\left.\begin{aligned} n_{rB} &= \frac{n_{eoB}}{1 - J_0\left(R\sqrt{\dfrac{\nu_{iB}}{D_{aB}}}\right)}\left\{J_0\left(r\sqrt{\frac{\nu_{iB}}{D_{aB}}}\right) - J_0\left(R\sqrt{\frac{\nu_{iB}}{D_{aB}}}\right)\right\} \\ \text{and} \qquad n_{eoB} &= \frac{g_B}{\nu_{iB} J_0 \sqrt{\alpha_B}}\,[1 - J_0\sqrt{\alpha_B}] \end{aligned}\right\} \tag{17 a}$$

Cummings and Tonks (1941), from their experimental observations have predicted that the normal distribution for a mercury arc plasma is not affected by the presence of a logitudinal magnetic field. Hence since the distribution is a function of ν/D_a we can assume that $\nu_i/D_a = \nu_{iB}/D_{aB}$. Consequently from eqns. (3) and (4)

$$\frac{i}{i_B} = \frac{E}{E_B}\,\frac{D_e}{D_{eB}}\,\frac{T_{eB}}{T_e}\,\frac{n_{eo}}{n_{eoB}} \tag{18}$$

Bickerton and Von Engel (1956) have shown that if T_{eB} is not much different from T_e the fractional change of energy of an electron to its total energy also remains constant with magnetic field. This leads us to $E/E_B = T_e/T_{eB}$. Hence

$$\frac{i}{i_B} = \frac{D_e}{D_{eB}}\,\frac{n_{eo}}{n_{eoB}} \tag{19}$$

Further if the change of electron temperature is small, then the rate of molecular ion formation due to associative ionization will almost remain the same so that $g = g_B$. The metastable population densities may be considered unaffected by the magnetic field. Hence since $\nu_i/D_a = \nu_{iB}/D_{aB}$ we get from eqns. (17) and (17 *a*) $n_{eo}/n_{eoB} = \nu_{iB}/\nu_i$. Then from eqn. (19)

$$\frac{i}{i_B} = \frac{D_e}{D_{eB}}\,\frac{\nu_{iB}}{\nu_i} \tag{20}$$

As we are considering electron impact ionization of highly excited states only, ν_i is as given by Elton (1970), from eqn. (8) and since $eX_i \ll KT_e$ we have

$$\frac{i}{i_B} = \frac{D_e}{D_{eB}}\sqrt{\frac{T_{eB}}{T_e}} \tag{21}$$

When the frequency of ionization is much less than the frequency of momentum transfer

$$D_{eB} = \frac{D_e}{1 + \omega_B{}^2\,\tau^2} = \frac{D_e}{1 + C_1(B^2/P^2)} \tag{20}$$

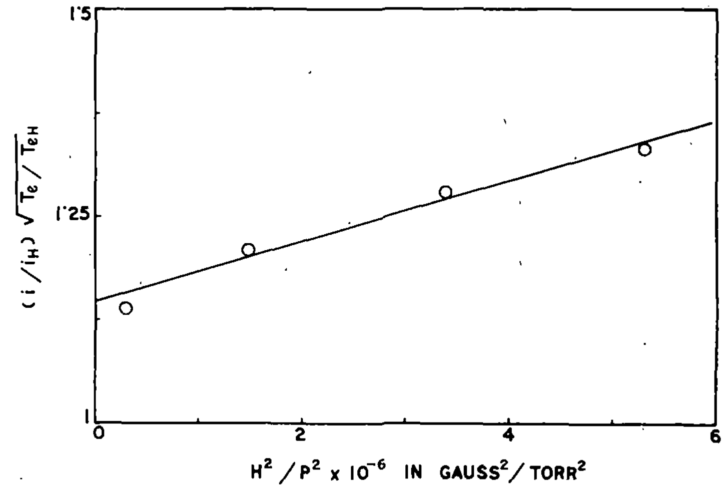

Figure 1. Variation of $(i/i_B)\sqrt{(T_e/T_{eB})}$ with B^2/P^2, $i=2{\cdot}5$ A.

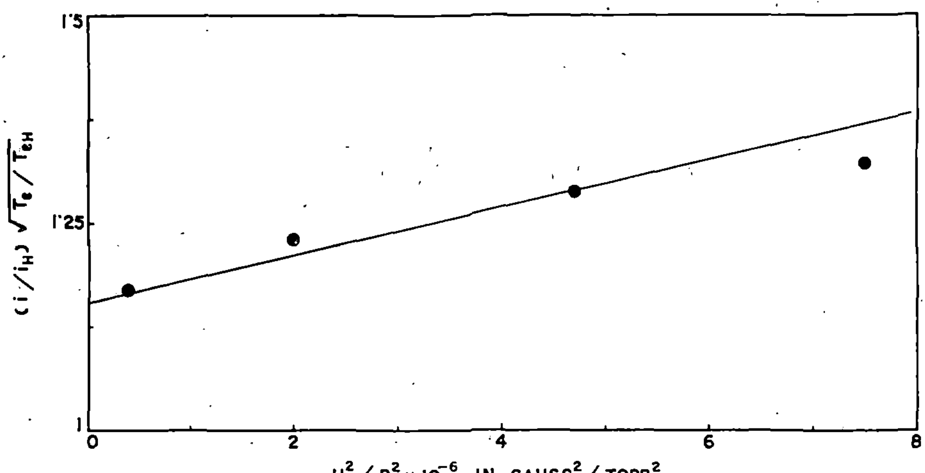

Figure 2. Variation of $(i/i_B)\sqrt{(T_e/T_{eB})}$ with B^2/P^2, $i=2{\cdot}25$ A.

where $C_1=[(e/m)(L/v_r)]^2$. L is the mean free path of an electron at a pressure of 1 torr, P is the total pressure and v_r is the random velocity. Hence from (19) and (20)

$$1+C_1\frac{B^2}{P^2}=\frac{i}{i_B}\left(\frac{T_e}{T_{eB}}\right)^{1/2} \tag{21}$$

A plot of $(i/i_B)(T_e/T_{eB})^{1/2}$ against B^2/P^2 (figs. 1 and 2) will be a straight line and the gradient determines the value of C_1 as entered in Table 5.

Magnetic field in gauss		$\frac{B^2}{P^2}\times 10^{-6}$	$\sqrt{\left(\frac{T_e}{T_{eB}}\right)_{expt}}$	$\left(\frac{i}{i_B}\right)_{expt}$	$\sqrt{\left(\frac{T_e}{T_{eB}}\right)}\left(\frac{i}{i_B}\right)$	C_1 from Figs 1 and 2
0	X	0	1	1	1	
	Y	0	1	1	1	
250	X	0·44	1·169	1·002	1·17	
	Y	0·3	1·138	1·0014	1·14	
550	X	2·0	1·2218	1·006	1·23	$0{\cdot}3\times10^{-7}=X$
	Y	1·47	1·2087	1·005	1·21	$0{\cdot}39\times10^{-7}=Y$
835	X	4·7	1·2564	1·0117	1·27	
	Y	3·4	1·2686	1·011	1·28	
1050	X	7·5	1·2915	1·0156	1·32	
	Y	5·3	1·302	1·017	1·33	

Table 5.

X corresponds to $i=2{\cdot}25$ A, $P_{air}=0{\cdot}08$ torr, $P_{Hg}=0{\cdot}3032$ torr
Y corresponds to $i=2{\cdot}5$ A, $P_{air}=0{\cdot}08$ torr, $P_{Hg}=0{\cdot}3731$ torr

4. Conclusion

Considering the physical processes involved in a mercury arc discharge where the buffer gas is air and the pressure is low, we have evolved a model in which air plays the role of quenching gas and have found that in this type of discharge both atomic and molecular ions of mercury are present. Assuming the existence of both types of ion we have obtained the distribution function and deduced an expression for T_e/T_{eB} (eqn. (21)), and have found that within the range of (B/P) values used here the experimental results are in quantitative agreement with the theoretical deduction.

That the electron temperature decreases in presence of an axial magnetic field in the case of mercury discharge has also been shown by Franklin (1976). $C_1=[(e/m)(L/v_r)]^2$ is evidently the square of the mobility of the electron in the mercury air mixture at 1 torr. The value of mobility calculated from C_1 agrees in order of magnitude with that obtained experimentally by Nakamura and Lucas (1978). Further the results show that frequency of ionization changes with the magnetic field as has been previously noted by Bickerton and Von Engel (1956).

It is also noted that $(n_{eoB}/n_{eo})=\sqrt{(T_e/T_{eB})}$, and as experimentally we have found that $T_e>T_{eB}$, then we will have $n_{eoB}>n_{eo}$ which was previously found to be true in the case of molecular gases, as determined by the probe method (Sadhya, *et al.* 1979, Cummings and Tonks 1941) in the case of mercury arc plasma.

Acknowledgments

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Appendix

The solution of eqn. (15)

$$D_a \frac{1}{r}\frac{d}{dr}\left(r\frac{dn_r}{dr}\right)+g+\nu_i n_r=0$$

can be obtained by putting $r/R=y$ and $n_r/n_{eo}=N_r$, where n_{eo} is the electron density at the axis. We then attain

$$\frac{d^2N_r}{dy^2}+\frac{1}{y}\frac{dN_r}{dy}+\frac{R^2}{D_a}N_r\nu_i+\frac{gR^2}{D_a n_{eo}}=0 \tag{22}$$

Let us first consider the equation

$$\frac{d^2N_r}{dy^2}+\frac{1}{y}\frac{dN_r}{dy}+\alpha N_r=0 \quad \text{where } \alpha=R^2\frac{\nu_i}{D_a}$$

Its solution is

$$y_1=J_0(\sqrt{\alpha}\cdot y) \tag{23}$$

with the condition $N_r=y_1=1$ at $y=0$ and we have,

$$\frac{d^2y_1}{dy^2}+\frac{1}{y}\frac{dy_1}{dy}+\alpha y_1=0 \tag{24}$$

Multiplying (22) by y_1 and (24) by N_r and subtracting we have

$$\frac{d}{dy}[y(y_1\dot{N}_r-N_r\dot{y}_1)]=-\beta y y_1 \tag{25}$$

where

$$\beta=\frac{gR^2}{n_{eo}D_a}$$

On integrating equation (25) with conditions that at $y=0$ both $\dot{N}_r$ and $\dot{y}_1=0$ we have

$$y_1\dot{N}_r-N_r\dot{y}_1=-\frac{\beta}{\sqrt{\alpha}}J_1(\sqrt{\alpha}\cdot y) \tag{26}$$

Dividing (26) by y_1^2 we get

$$d\left(\frac{N_r}{y_1}\right)=-\frac{\beta}{\alpha}\frac{d[J_0(\sqrt{\alpha}y)]}{[J_0(\sqrt{\alpha}y)]^2} \tag{27}$$

Integrating (27) with conditions $y=1$, $N_r=0$

$$N_r=\frac{g}{n_{eo}\nu_i}\left[\frac{J_0(\sqrt{\alpha}y)}{J_0(\sqrt{\alpha})}-1\right] \tag{28}$$

Now at $y=0$, $N_r=1$ so eqns. (17) and (16), in the text, follow.

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