CHAPTER - IV.

PLASMA PARAMETERS FROM RADIOFREQUENCY CONDUCTIVITY MEASUREMENTS

INTRODUCTION.

The possibility of the use of a r.f. signal as a probe in the study of the electrical discharge phenomena in the steady state was first suggested by Vander Pol (1919). If a r.f. voltage, not sufficient to cause the breakdown, be applied to ionize the gas then the r.f. current $I_{r.f}$ that flows through the gas is given by

$$I_{r.f} = \frac{e^2 n X_0}{m}\left[\frac{\nu_c}{\nu_c^2+\omega^2} - j\frac{\omega}{\nu_c^2+\omega^2}\right]$$

where n is the number of electrons per cc of the ionized medium, e and m the charge and mass of the electron respectively; $X_0 e^{j\omega t}$ the radiofrequency field applied, ω the angular frequency of applied field; ν_c the collisional frequency of the electrons. Hence the complex conductivity is given by

$$\sigma_c = \frac{I_{r.f}}{X_0} = \frac{e^2 n}{m}\left[\frac{\nu_c}{\nu_c^2+\omega^2} - j\frac{\omega}{\nu_c^2+\omega^2}\right]$$

$$\sigma_c = \sigma_r - j\,\sigma_i$$

so that $$\sigma_r = \frac{e^2 n\,\nu_c}{m[\nu_c^2+\omega^2]} \quad \text{and} \quad \sigma_i = \frac{e^2 n\,\omega}{m[\nu_c^2+\omega^2]} \qquad (4.1).$$

It is thus seen that both σ_r and σ_i are functions of (i) frequency ω, (ii) electron density n and (iii) the collision frequency ν_c which itself is a function of pressure. The value of σ_r is maximum when $\nu_c = \omega$ in which case $\sigma_r/\sigma_i = 1$. Thus by measuring the conductivity of an ionized gas in a high frequency field, the electron concentration can be obtained. The conductivity of ionized air was measured by Childs (1932) by substitution of a resistance of known value for the leakage resistance of the ionized gas, the oscillation frequency being 1 Mc/sec. Appleton and Chapman studied the variation of the radiofrequency conductivity of ionized air with pressure at frequency of the order of 1000 Mc/sec using a Lecher wire system coupled to the condenser within which the discharge tube was placed. Appleton and Chapman (1932) observed that the conductivity attains a maximum value at a certain pressure and then decreases in accordance with the theory. But they have not reported any absolute value of conductivity for the gas investigated, namely air. The same study was made in case of sulphur dioxide and neon by Imam and Khastgir (1937) in the pressure range 10-100 cm. of Hg. using radio waves of $\lambda = 481$ cm. and a Lecher wire system. The simple theory ~~attained~~ described above has been modified by Margenau (1946) by taking into consideration the distribution of velocities and employing Boltzman Transport equation. The modified expression for σ is given by

$$\sigma = \frac{4}{3}\frac{ne^2\lambda_e}{\sqrt{2\pi m K T_e}}\cos\omega t + \frac{ne^2\lambda_e^2\,\omega}{3KT_e}\sin\omega t$$

$$\text{for values of } \nu_c \gg \omega \qquad (4.2).$$

From a study of the complex conductivity of mercury vapour at microwave frequencies Adler (1949) has obtained the variation of σ_r and σ_i with current and pressure when one is kept at a constant value. Using the theoretical expression of Margenau, Adler calculated values of the electron density in the discharge and compared the values thus obtained with those obtained experimentally using Langmuir probe measurements. Adler found that the theoretical and experimental values agree closely and that n varies linearly with the discharge current.

The presence of magnetic field changes the various characteristics of discharge; it is natural to suppose that the radiofrequency conductivity of an ionized gas will also change in presence of a magnetic field. Conductivity of ionized gas such as air, nitrogen and hydrogen in a magnetic field was measured by Ionescu and Mihul (1932) for pressure greater than 10^{-3} mm. of Hg., who found that maxima other than those due to free electrons coluld be obtained. With very intense fields, only the variation due to free electrons remained, the others disappearing and the values of the magnetic field giving maximum conductivity varied with pressure. A theory regarding the variation of radiofrequency conductivity with magnetic field was proposed by Appleton and Bochariawala (1935) who showed that the real part of radiofrequency conductivity in a magnetic field is given by

$$\sigma_{rH} = \frac{ne^2}{m^*} \frac{\nu_c\left(\omega^2 + \omega_b^2 + \nu_c^2\right)}{\left(\omega^2 + \omega_b^2 + \nu_c^2\right)^2 - 4\omega^2\omega_b^2}$$

when n is the number of electrons per unit volume and ν_c the collision frequency ω the angular frequency of the applied field and $\omega_b = \frac{eH}{m}$; from graphical analysis, it was shown by the authors that the value of ν_c for which the conductivity becomes a maximum is obtained when $\omega_b/\omega = 1$ i.e. when $\nu_c = 0$ which is anomalous and further the experimental results obtained by the authors were not supported by the theory developed; but it was conclusively shown that the magnetic field has a marked influence on the pressure at which the conductivity becomes maximum and the value of the conductivity changes when the magnetic field is applied. A general theory regarding the variation of radiofrequency conductivity of ionized gases and its variation with pressure and magnetic field has been worked out by Gilardini (1959) who derived the expression for the conductivity of an ionized gas under the following assumptions :

(a) when the distribution function is predominatly spherically symmetrical in velocity space but not necessarily Maxwellian.

(b) When the electron collision frequency is an arbitrary function of electron velocity.

The value of the complex conductivity is given by

$$\sigma = \frac{e^2 n}{m} \frac{1}{\nu_c + j\omega}$$

In presence of magnetic field he has defined two conductivities; a conductivity σ_r for the right handed polarization and a conductivity σ_0 for the left-handed polarization.

where $$\sigma_c' = \frac{e^2 n}{m}\left[\frac{1}{\nu_c + j(\omega - \omega_b)}\right]$$

and $$\sigma_o = \frac{e^2 n}{m}\left[\frac{1}{\nu_c + j(\omega + \omega_b)}\right]$$

and the conductivity in the direction of the field is given by

$$\sigma_H = \frac{1}{2}\left(\sigma_c + \sigma_o\right)$$

$$= \frac{1}{2}\frac{e^2 n}{m}\left[\left\{\frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2}\right\} - j\left\{\frac{\omega - \omega_b}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\omega + \omega_b}{\nu_c^2 + (\omega + \omega_b)^2}\right\}\right]$$

so that real part of the conductivity is given by

$$\sigma_{rH} = \frac{e^2 n}{2m}\left[\frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2}\right]$$

and after simplification it reduces to the result obtained earlier by Appleton and Boohariwalla (1935)

$$\sigma_{rH} = \frac{e^2 n}{m}\,\frac{\nu_c\left(\nu_c^2 + \omega_b^2 + \omega^2\right)}{\left(\nu_c^2 + \omega_b^2 + \omega^2\right)^2 - 4\omega^2\omega_b^2}$$

...(4.3).

Though some measurements of radiofrequency conductivity have been carried out earlier it is felt necessary that a thorough and systematic experimental measurement of radiofrequency conductivity of ionized gases in a magnetic field will yield some data which can be utilized for the verification of the theory advanced by Gilardini (1959) or by Appleton & Boohariwalla it will also be of interest to study the variation of radio-frequency conductivity in a magnetic field and to see how the pressure at which the conductivity becomes a maximum varies with the application of the magnetic field. A theory for the radiofrequency conductivity has been developed to explain the observed results in case of number of gases such as air, carbon dioxide, hydrogen, helium, neon and argon in a magnetic field which has been varied from 0 to 680 gauss and the pressure varying from few microns upto 700 μ .

From the measurements of radiofrequency conductivity of ionized gases, it is possible to calculate plasma parameters, such as collision frequency, electron density, electron temperature, Debye shielding distance, dielectric constant etc. of the discharge. A precise knowledge of these parameters, their variation with pressure, discharge current and externally applied magnetic field is essential for the proper understanding of the mechanism operating in the discharge. As pointed out earlier, some measurements of this nature have been carried out in the microwave region but the data in the radiofrequency region is very rare. The present method further supplements the standard methods in plasma diagonistics and gives accurate values and helps in elucidation of the nature of variation of these parameters in an externally applied field also. The advantage of the method over the probe method lies in the fact that whereas in the probe method the plasma is disturbed by the introduction of the probe, the measurements of radiofrequency conductivity does not alter any of the parameters of the discharge.

THEORY OF MEASUREMENT AND EXPERIMENTAL ARRANGEMENT.

The experimental procedure followed in the present investigation for the determination of conductivity of an ionized gas is different from that adopted in earlier methods and hence the theory of the experiment is outlined below.

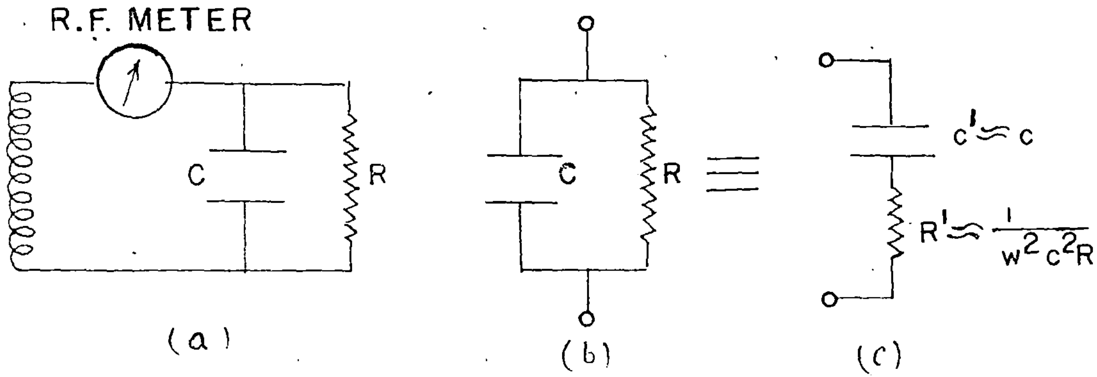


Fig- 4·1

The r.f. voltage from an oscillator was supplied to the ionized gas through a coupled circuit (fig. 4.1) consisting of an r.f. milliammeter and a variable condenser (100 P.F.) in series. Two rectangular metal plates (10 x 3.75 cm.) fixed parallel to each other formed a condenser in parallel with variable condenser. The discharge tube was mounted within the parallel plate condenser and the condenser plates were fixed touching the two sides of the tube. Before the mounting of the discharge tube if E_1 is the voltage developed across the condenser for an observed value of the current I_1 at resonance, then

$$I_1 = E_1 \omega C \qquad \text{...(4.4).}$$

where C is the capacity of the fixed condenser in absence of the discharge tube; when the discharge tube is placed within the condenser C , two effects are introduced, (i) the dielectric constant of the consenser is changed and (ii) the ionized gas acts as a lossy resistance in parallel to the condenser, so that when the discharge is on, the secondary circuit is modified as shown in fig. 4.1(a), the equivalent circuit for that part of circuit right of the meter is shown in fig. (4.1b). The out put impedances for the two alternative circuits in fig. (4.10) are

$$Z_p = \frac{R}{1 + j\omega C R} \qquad \text{in case of the parallel combination}$$

and $$Z_p = R' - \frac{j}{\omega C} \qquad \text{in case of the series combination}$$

Since the output impedances of the two alternative circuits are to be equivalent,

$$\frac{R}{1 + j\omega C R} = R' - \frac{j}{\omega C}$$

$$\frac{R}{1 + \omega^2 C^2 R^2} = R' \quad \text{and} \quad \frac{\omega C R^2}{1 + \omega^2 C^2 R^2} = \frac{1}{\omega C'}$$

Now in general $\omega^2 C^2 R^2 >> 1$ and so $C \approx C'$ and $R' = \frac{R}{\omega^2}$

The change of dielectric constant of the condenser will be very small, especially for low density plasma and it can be counteracted by adjusting the variable Condenser. In actual experiment we have noted that this change is insignificant. Hence the current in the meter when the discharge is on is given by

$$I_2 = \frac{E_2}{\sqrt{R'^2 + 1/\omega^2 C^2}} \qquad \ldots(4.5)$$

where E_2 is the voltage across the condenser when the discharge is on. From equations (4.4) and (4.5) it can be shown that

$$R' = \left[\frac{E_2^2}{I_2^2} - \frac{E_1^2}{I_1^2}\right]^{1/2}$$

The voltages E_2 and E_1 are measured with V.T.V.M. (Marconi) and I_1 and I_2 are obtained with the radiofrequency millimmeter attached with the circuit. After obtaining R', R can be calculated from the relation

$$R' = 1/\omega^2 C^2 R$$

If S represents the area of the discharge tube presented to the radiofrequency field introduced inside the condenser, and t the thickness of the tube then

$$R = \rho\, t/S$$

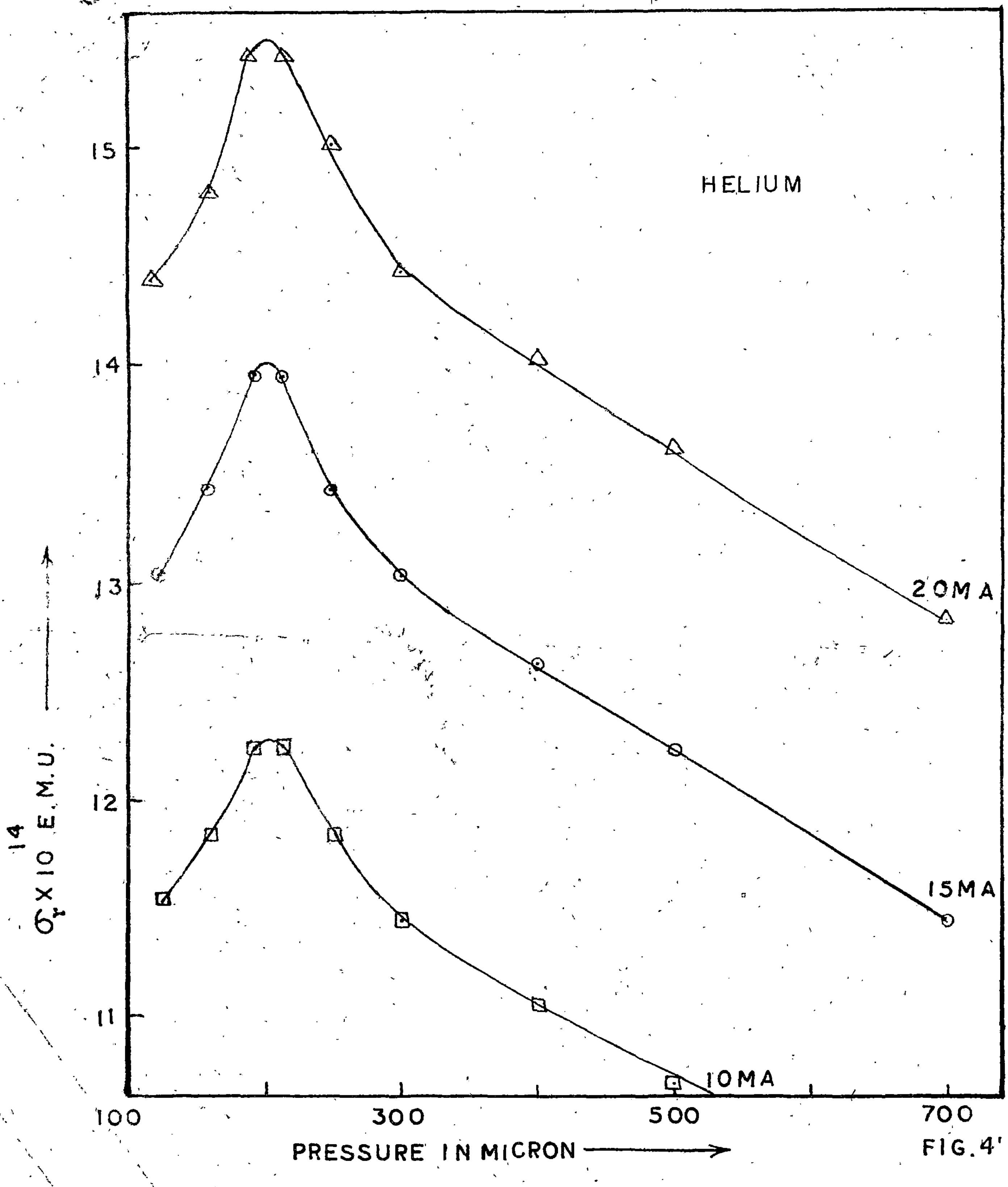
and σ_r the conductivity will be given by

$$\sigma_r = 1/\rho = t/RS$$

A stabilised power supply supplies power to the oscillator (tuned plate tuned grid type) working in the frequency range 4–20 Mc/Sec. The frequency at which the present measurements have been carried out has been measured to be 10.6 Mc/Sec. The output of the oscillator is connected to the two ends of the primary circuit and the secondary circuit is coupled to it. The discharge tube consists of a long cylindrical glass tube fitted with two electrodes and the discharge is excited by means of a transformer (10KV). The pressure has been very carefully measured by an Edward Pirani Penning vacuum gauge. Pure and dry air has been used and carbondioxide has been prepared by letting a saturated solution of oxalic acid in water fall drop by drop into saturated solution of sodium bicarbonate (analytical grade). The evolved gas was passed through phosphorus pentoxide to remove water. Spectroscopically pure helium, neon and argon have been supplied by the British Oxygen Company. The magnetic field has been supplied by an electromagnet and the lines of force are perpendicular both to the direction of the field and to the length of the discharge tube. The magnetic field has been varied from 0 to 680 gauss. Before starting the discharge the Tank current (I_1) and the corresponding voltage (E_1) is measured by means of a valve voltmeter. The discharge is then started and the discharge current is kept constant while the pressure within the discharge tube is varied. The corresponding values of I_2 and E_2 are noted in each case. The observations are made during two series of experiments, (i) in which the discharge current is kept constant (at 10, 15, 20 ma) while the pressure of the gas is varied from few microns upto 700μ and (ii) keeping the magnetic field constant at a particular value while the discharge current is kept constant at 10 ma for He, Ne, A & H_2 and 20 ma for air CO_2 the pressure of the gas has been varied. The same procedure has been repeated for different values of the magnetic field. The experiments have been repeated a large number of times and the data have been found to be consistent.

RESULTS AND DISCUSSION.

The variation of σ_r, the real part of radiofrequency conductivity with pressure has been plotted in figure (4.2 to 4.7) for helium, neon, argon, hydrogen, air and carbondioxide for three different values of the discharge current namely 10 mA, 15 mA, 20 mA. In all the gases studied, the radiofrequency conductivity gradually increases with pressure, attains a maximum value at a


HELIUM
20MA
15MA
10MA
15
14
13
12
11
$\sigma_r \times 10^{14}$ E.M.U.
100
300
500
700
PRESSURE IN MICRON
FIG. 4'2

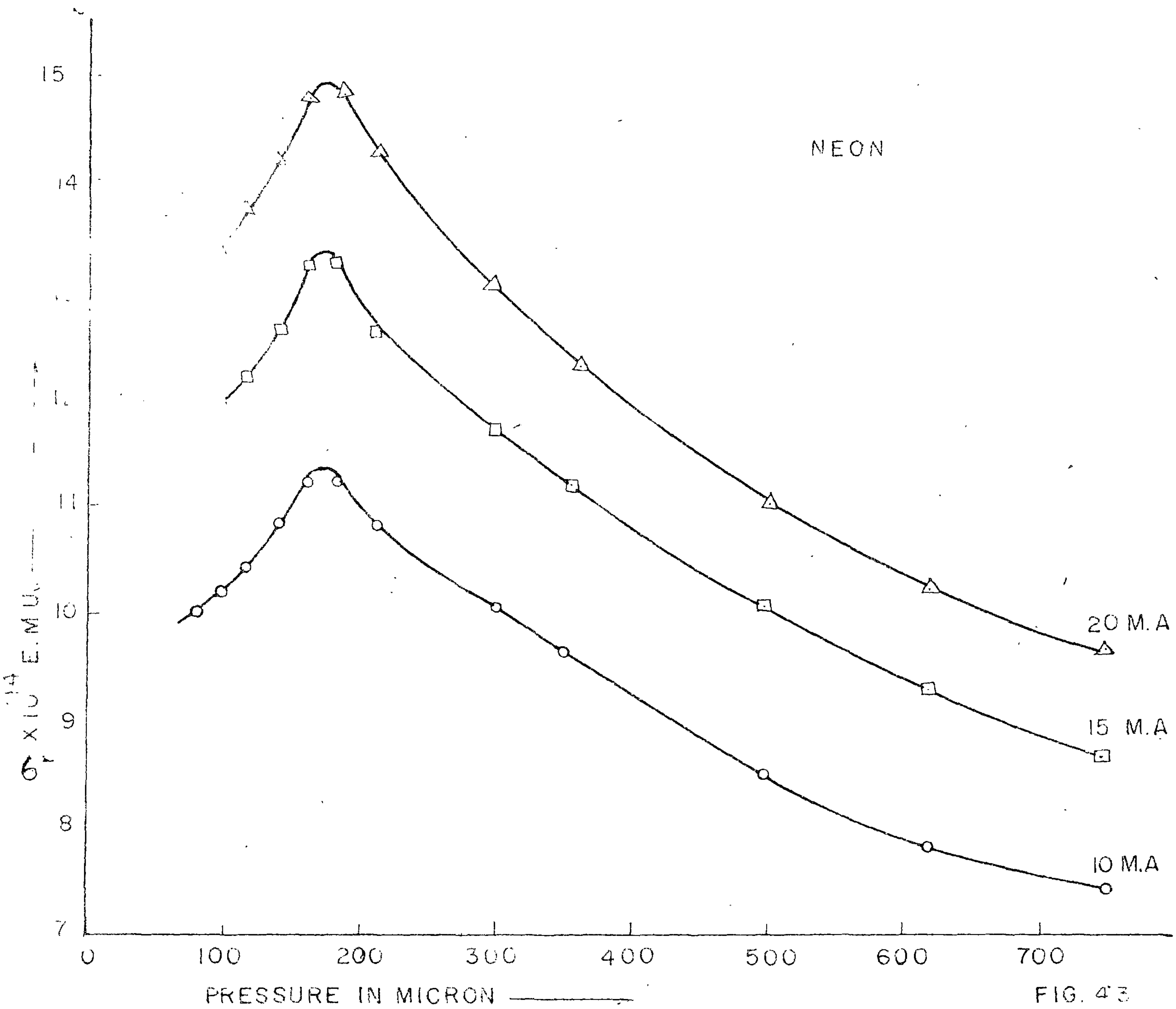
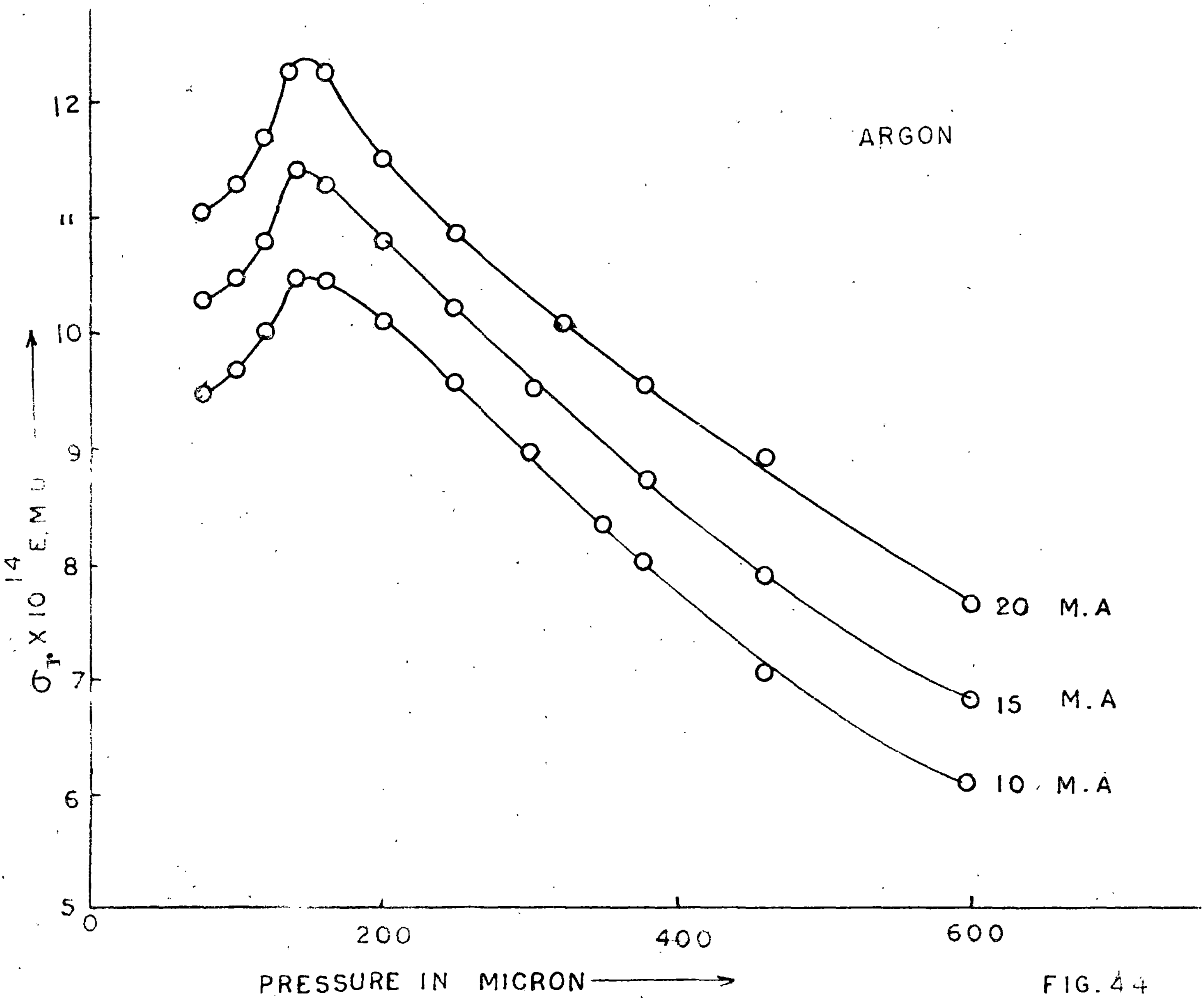
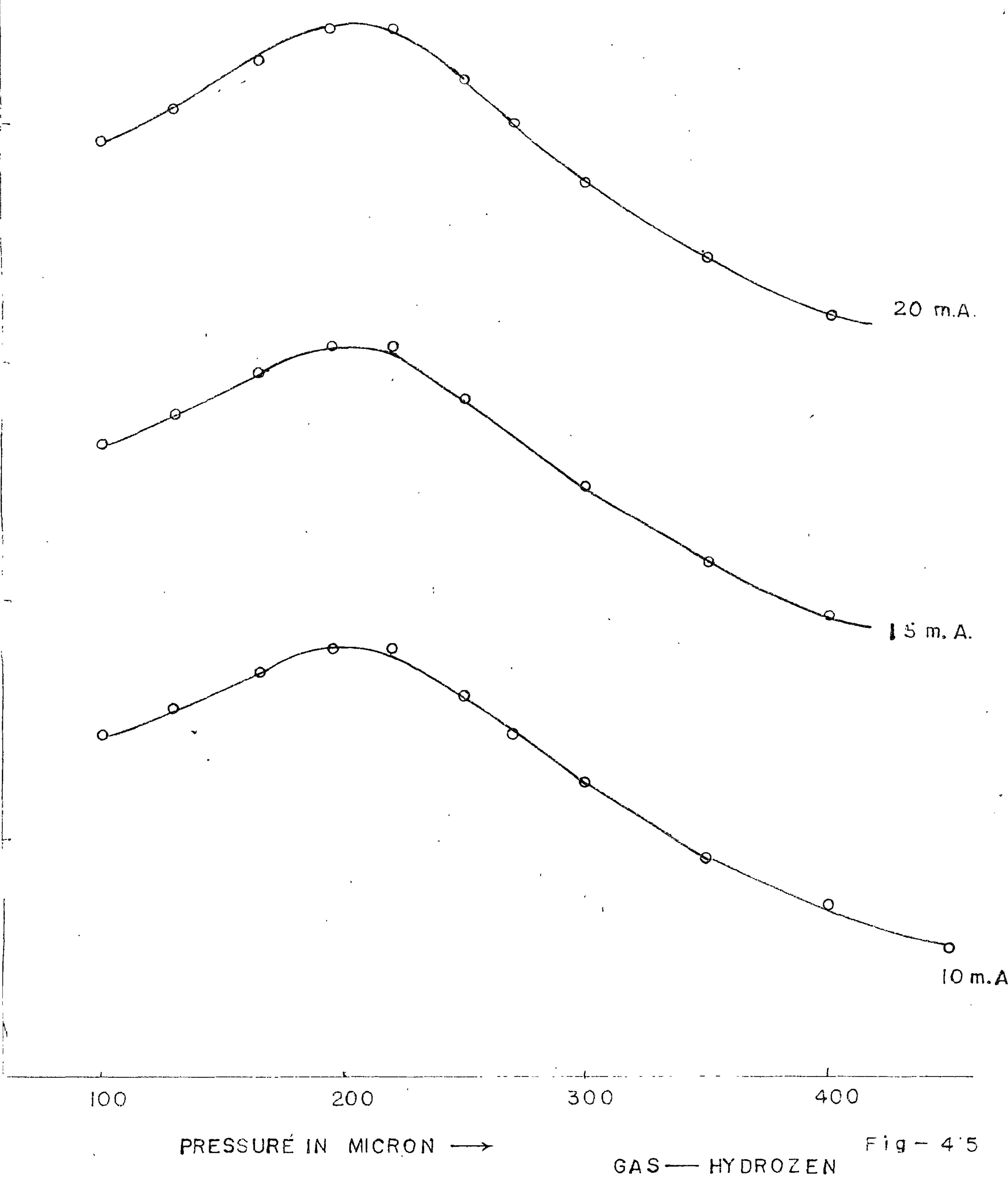

NEON
20 M.A
15 M.A
10 M.A
15
14
11
10
9
8
7
0
100
200
300
400
500
600
700
PRESSURE IN MICRON
6 X 10^14 E.M.U.

FIG. 43



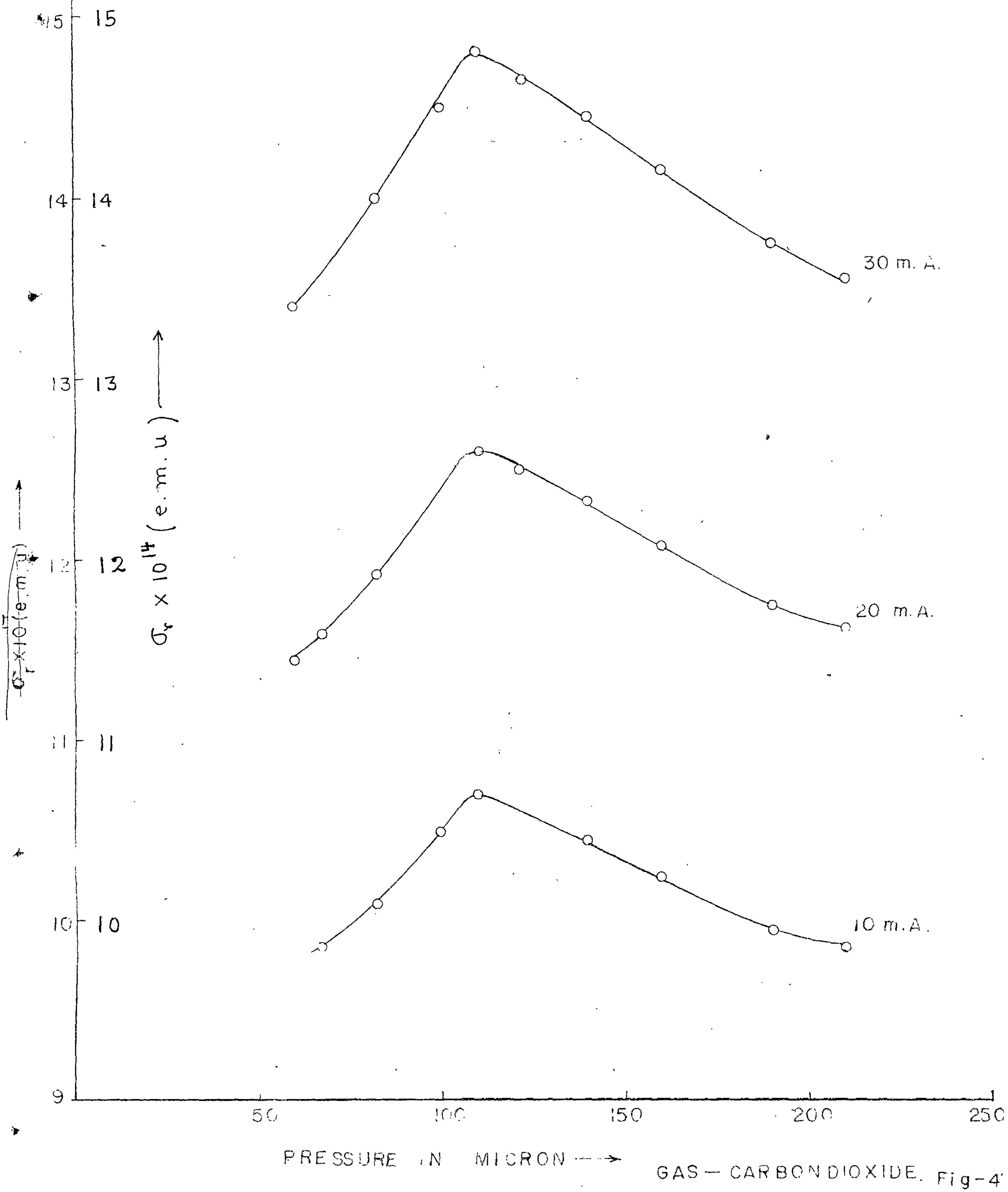
ARGON
$\sigma_T \times 10^{14}$ E.M.U
PRESSURE IN MICRON
20 M.A
15 M.A
10 M.A

FIG. 44

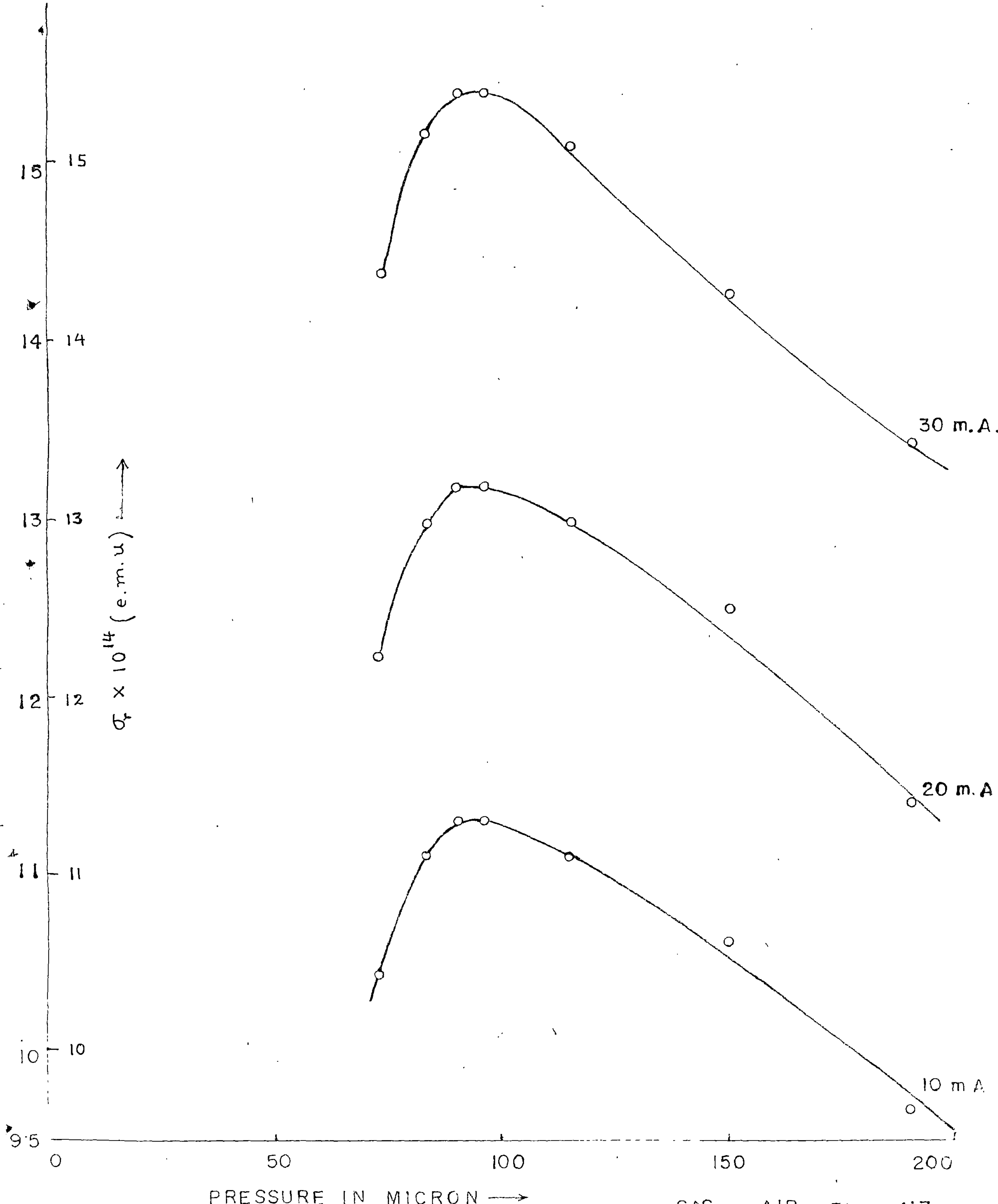


20 m.A.
15 m. A.
10 m.A
100
200
300
400
PRESSURE IN MICRON ⟶
GAS — HYDROZEN

Fig - 4.5



GAS — CARBONDIOXIDE. Fig-4



GAS — AIR Fig – 4·7

certain pressure which is different for different gases and then gradually falls in accordance with the formula (Sen and Ghosh 1964)

$$\sigma_r = \frac{n e^2}{m} \frac{\nu_c}{\nu_c^2 + \omega^2}$$

It is observed that the maximum value of conductivity occurs at the same pressure for different values of the discharge current. The condition for σ_r to be maximum is obtained when $\nu_c = \omega$ which is valid only when the electron density does not change with pressure. Appleton and Chapman (1932) using a Langmuir probe showed that n does not change with pressure. Since n can be taken as a measure of the degree of ionization, change of pressure alone will not materially affect the value of n and it can be regarded as a constant to a first approximation when the pressure is gradually changing. Since the applied frequency does not change, the maxima should occur at the same value of pressure irrespective of discharge current. The value of n can then be calculated from the relation.

$$(\sigma_r)_{max} = \frac{n e^2}{2 m \omega} \qquad ...(4.6).$$

Such values for n, for the pressure for which $\nu_c = \omega$ have been computed and entered in table (4.1) for all the six gases and for different discharge currents. From table (4.1) it is evident that n is not proportional to discharge current but has a tendency to assume a saturation value as the current increases, in case of all the six gases, which is also evident from the ratio (n/i) entered into the last column of table (4.1). Since the current $i = nev$, it follows that the velocity v of the electron should increase due to increase voltage applied to get higher discharge currents.

TABLE - 4.1

Calculated values of electron density n at different values of discharge current.

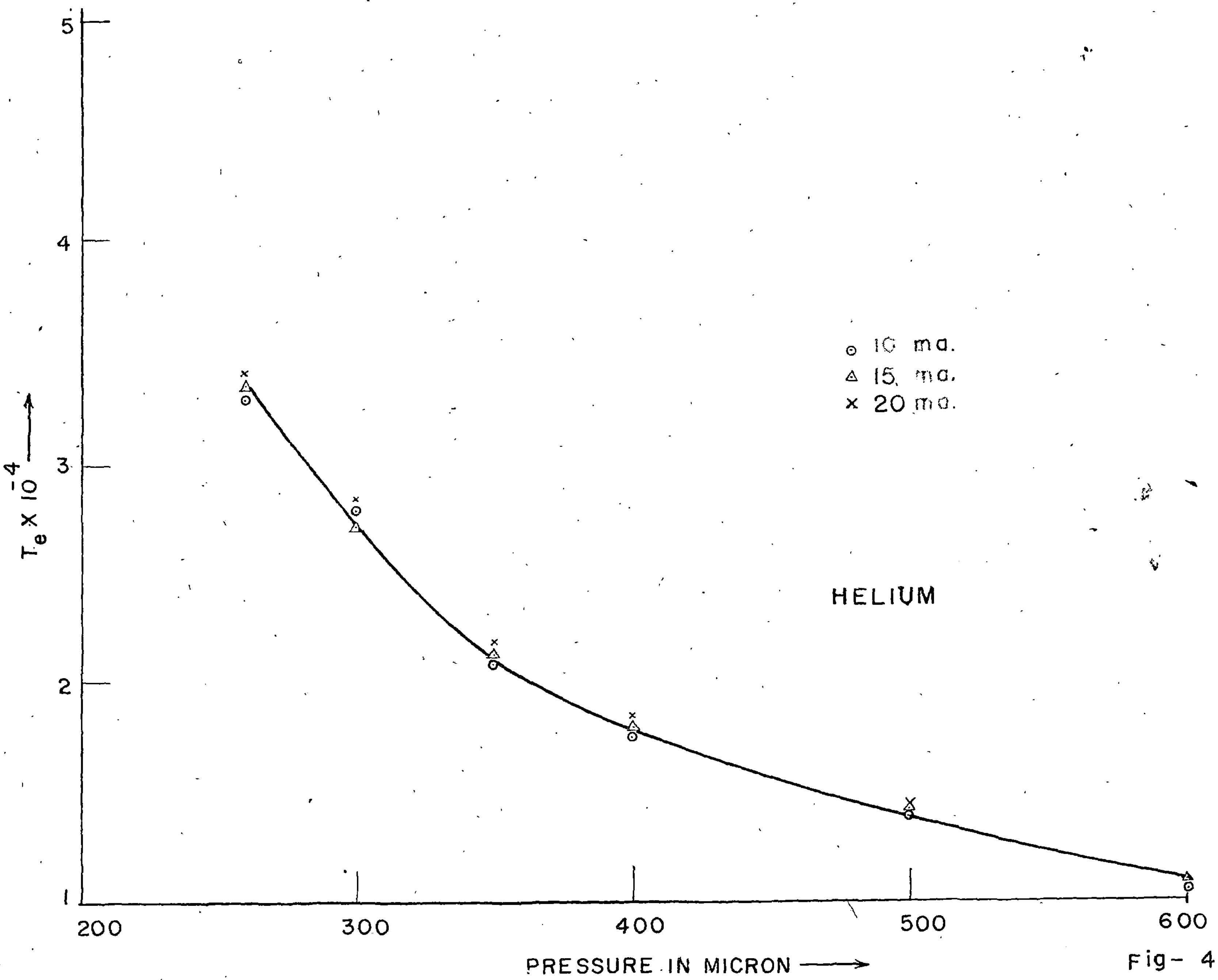
Gas	Discharge current in mA.	Pressure in micron for $(\sigma_r)_{max}$	$(\sigma_r)_{max} \times 10^{14}$ e.m.u	$n \times 10^{-8}$ as calculated from Eqn. (1).	$(n/i) \times 10^{-10}$
	10		10.5	.468	.468
Argon	15	145	11.42	.5108	.3405
	20		12.45	.5433	.2717
	10		11.25	.5025	.5025
Neon	15	170	13.3	.594	.396
	20		14.95	.6674	.3337
	10		12.28	.5485	.5483
Helium	15	200	14.02	.625	.417
	20		15.5	.692	.346
	20		13.4	.598	.30
H_2	15	210	12.06	.538	.36
	10		10.8	.481	.48
	30		15.41	.690	.23
Air	20	92	13.18	.588	.294
	10		11.3	.504	.50
	30		14.8	660	.22
CO_2	20	108	12.6	562	.28
	10		16.7	476	.476

as $\sigma_r = \frac{ne^2}{m} \frac{\nu_c}{\nu_c^2 + \omega^2}$ and $(\sigma_r)_{max} = \frac{ne^2}{2m\omega}$

it can be deduced that

$$\nu_c = \omega \left[\frac{(\sigma_r)_{max}}{\sigma_r} \pm \sqrt{\frac{(\sigma_r)^2_{max}}{(\sigma_r)^2} - 1} \right] \quad \text{...(4.7).}$$

Hence it is possible to calculate the collision frequency of the electron at different pressures for different gases and from the relation $\nu_c = \frac{\upsilon_r}{\lambda_e}$ where λ_e is the mean free path of the electron in the gas, υ_r can be calculated. λ_e has been calculated from the relation $\lambda_e = L/p$ where L is the mean free path of the electron in the gas at a pressure of 1 mm and $L = 1/A_o$ where A_o is the coefficient introduced by Townsend in his theory of electrical breakdown of gas. The values of A_o for different gases have been obtained from Von Engel (1955). Further, since $\upsilon_r = \sqrt{\frac{8KT_e}{m\pi}}$, the value of electron temperature can be calculated and the values thus obtained have been plotted in figure (4.8 - 4.13) against the corresponding pressure for helium, neon, argon, air, carbondioxide and hydrogen respectively. The variation of electron temperature with pressure indicates that the fall is rather rapid at low pressure but at higher pressure it practically remains unchanged. The nature of variation is the same in case of all the gases studied here as was found previously by Sen and Ghosh (1964) in case of air and nitrogen. The results are also quite similar to those obtained in case of arc plasma by Bohm et al (1949) and further it is noted that there is little variation of electron temperature with the change of discharge current. The change with pressure has been ascribed by Bohm et al to the greater number of inelastic collisions which the electron suffers with the gas molecules and as an appreciable fraction of electrons will posses energy sufficient to excite and even to ionize the gas molecules, it is expected that the electron temperature which is a measure of the remaining energy of the electrons will decrease with the increase of pressure; because due to increasing number of inelastic collisions, the energy transferred by the electrons to the atoms will increase.



5
4
3
2
1
$T_e \times 10^{-4}$
⊙ 10 ma.
△ 15 ma.
× 20 ma.
HELIUM
200
300
400
500
600
PRESSURE IN MICRON

Fig- 4·8

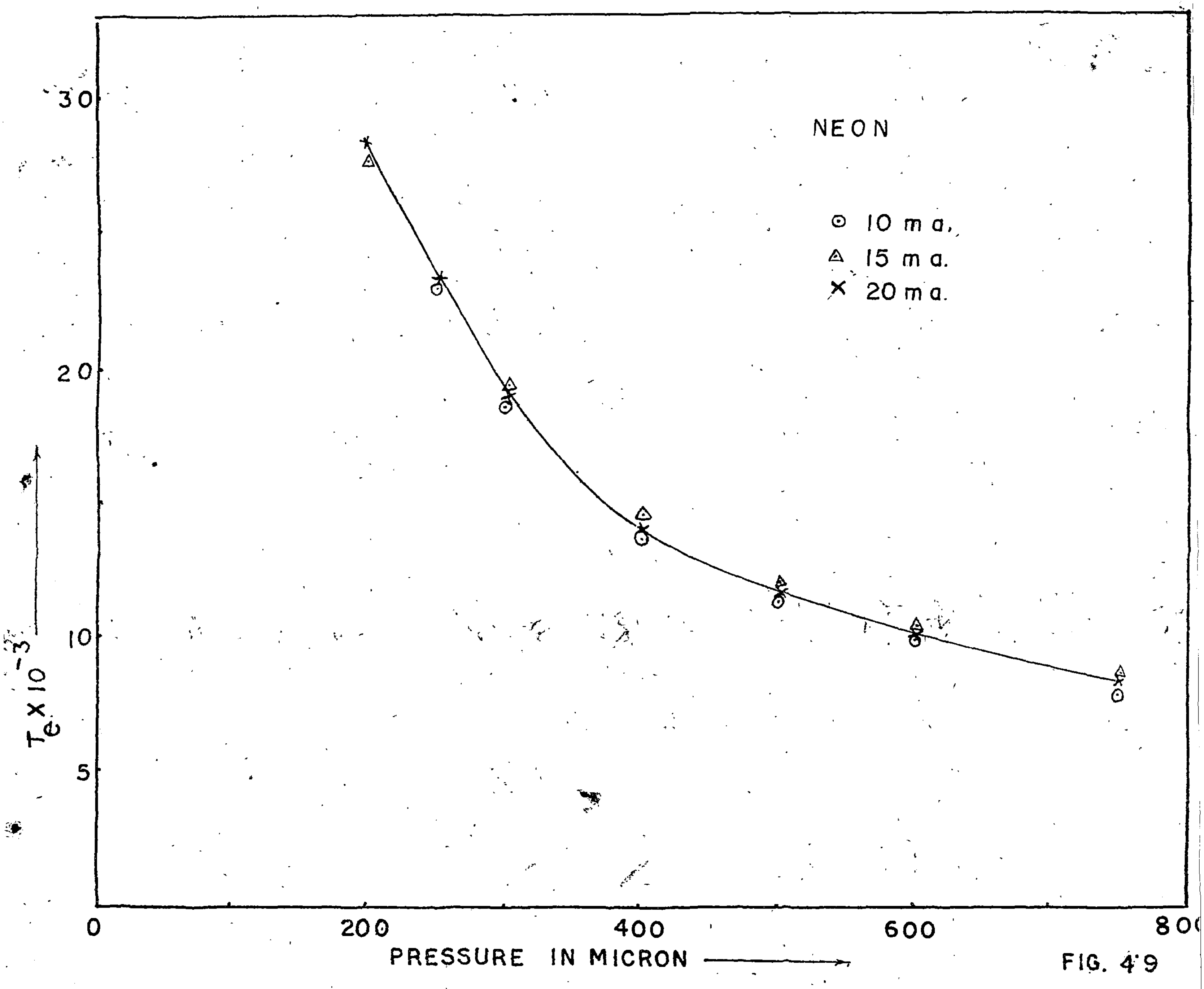

NEON
10 m a.
15 m a.
20 m a.
30
20
10
5
$T_e \times 10^{-3}$
0
200
400
600
800
PRESSURE IN MICRON

FIG. 4·9

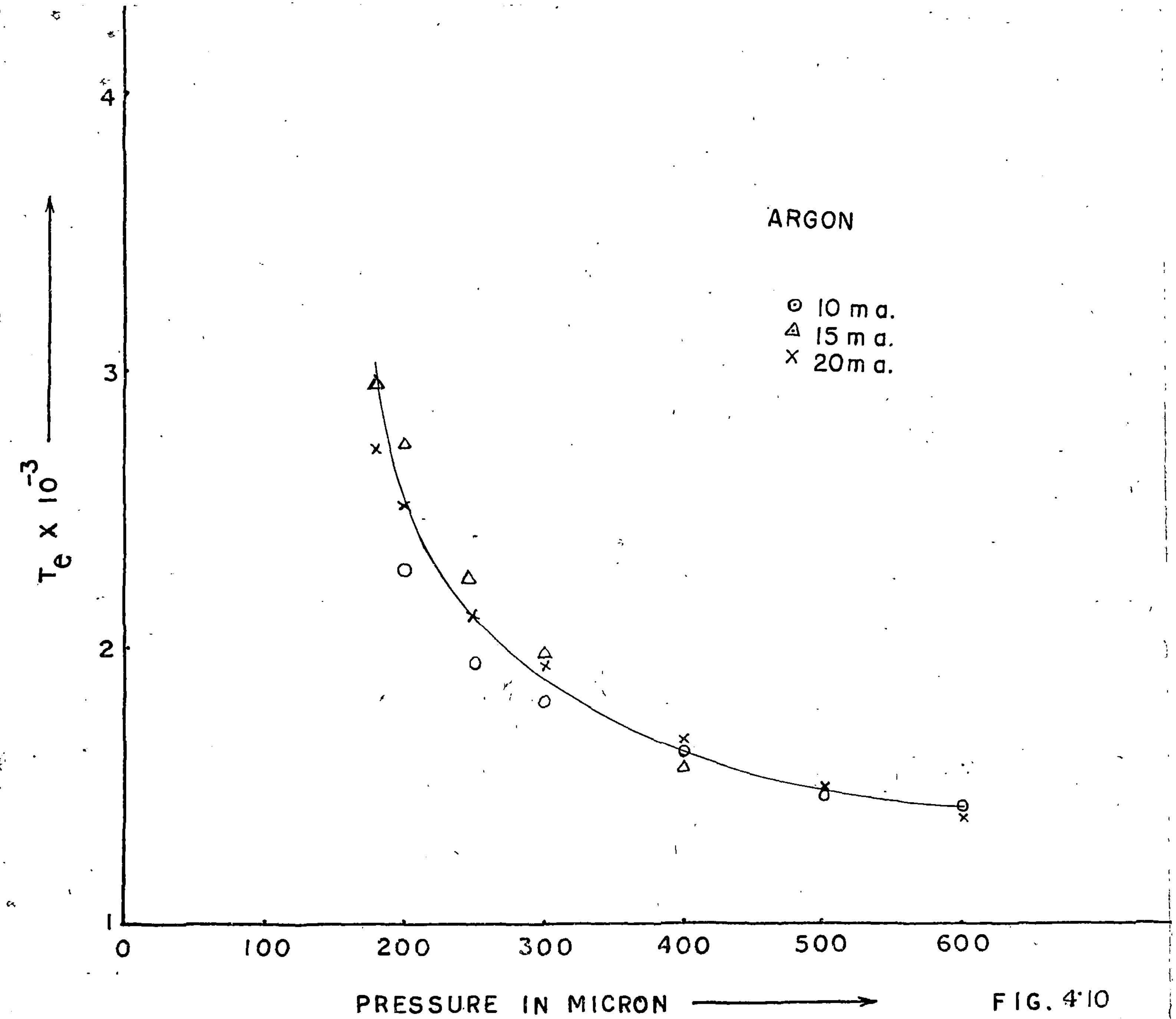

ARGON
10 ma.
15 ma.
20ma.
$T_e \times 10^{-3}$
4
3
2
1
0
100
200
300
400
500
600
PRESSURE IN MICRON

FIG. 4·10

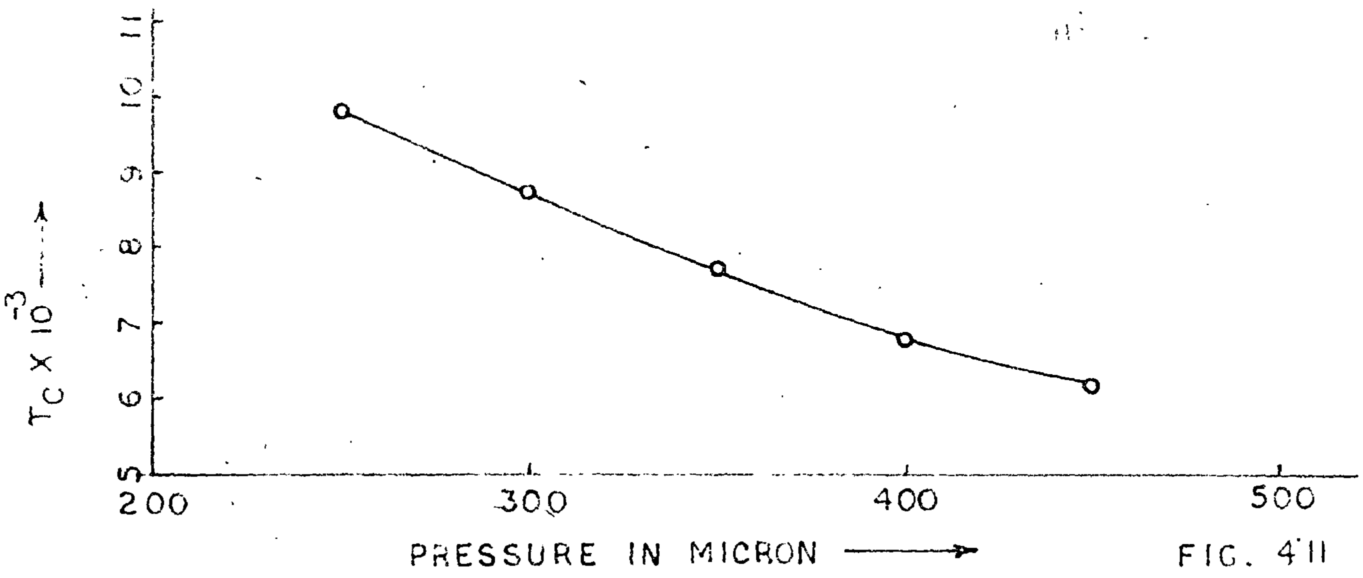
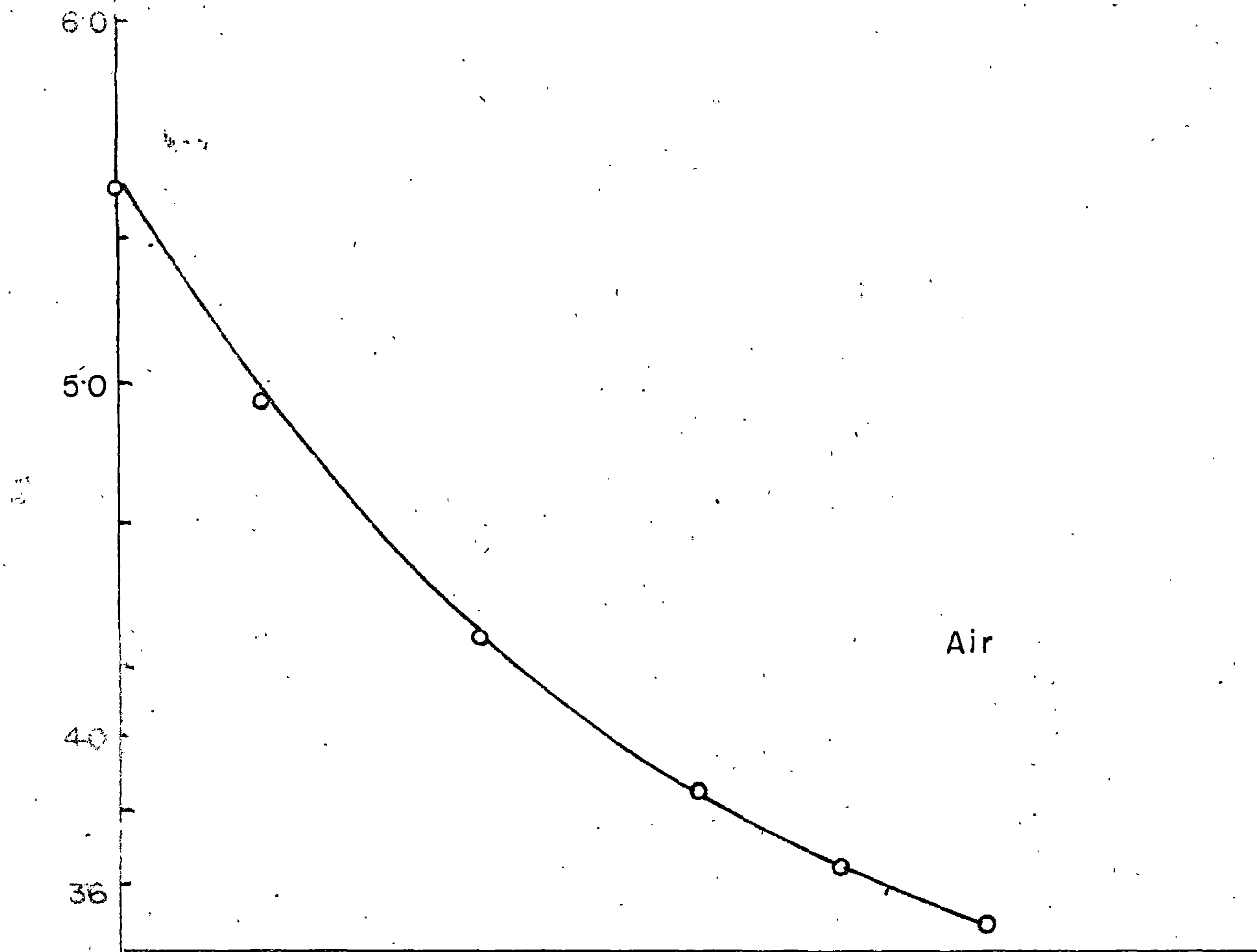


FIG. 4.11



Fig— 4·12

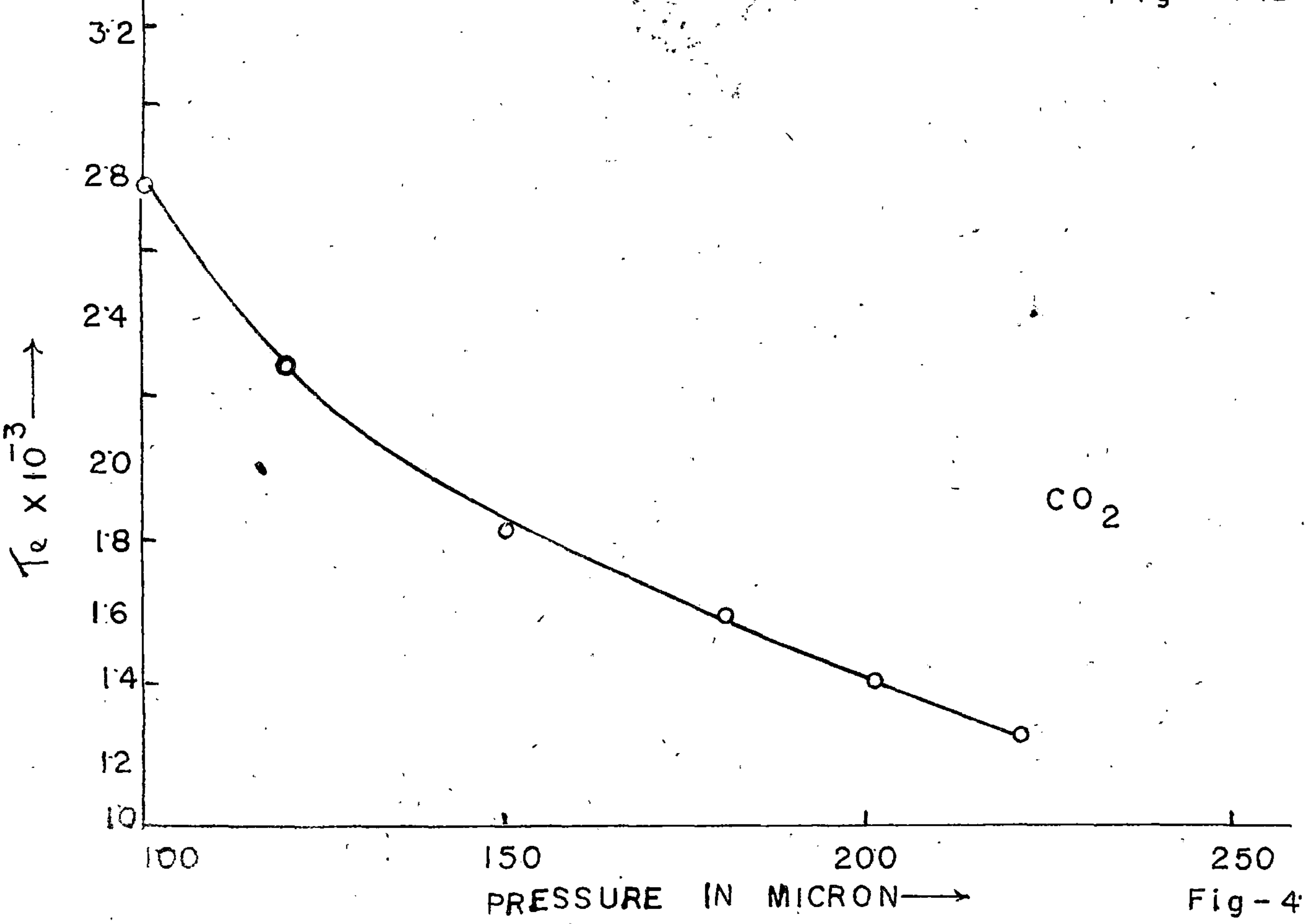


Fig-4·13

It has been found that the Maxwellian distribution is a good approximation for molecular gases where the excitation levels including the vibrational ones are widely spread out upto ionization level. Hence inelastic losses set up at relatively low energies and though the average electron energy is low, the losses are so distributed as to produce an approximately Maxwellian distribution. In rare gases however, the excitation levels are much closer to ionization level and hence for low values of $E/_p$, only elastic losses are important. The average energy is much higher than in molecular gases at the same value of $(E/_p)$ and Druyvestyn distribution holds. The fact that the electron temperature becomes practically constant for large values of pressure can be explained by the fact that elastic losses predominate and there is no change of electron energy. Further as $\nu_c = v_r/\lambda_e$ and due to Townsend Ramsauer effect λ_e is not a constant but varies with the electron energy, the random velocity and hence the electron temperature becomes a function of pressure.

Margenau (1946) assuming only elastic collisions and a constant mean free path found an energy distribution expressed by an expansion whose first two terms represent a Maxwellian and Druyvestyn distribution respectively. In a d.c. field, the Maxwellian term is zero and the resulting distribution is approximately Druyvesteyn. For a constant mean free time the electron temperature is given by

$$T_e = T_{gas} + \frac{M e^2 E_0^2}{6 K m^2 (\nu_c^2 + \omega^2)}$$

where M = mass of the gas molecule, E_0 is the breakdown voltage applied per cm, ν_c the collision frequency; as ω the excitation frequency is also of the order of 10^7 cycles/Sec.

$$T_e \approx T_{gas} + \frac{M e^2 E_0^2}{12 K m^2 \nu_c^2}$$

assuming $\nu_c = \omega = 6.28 \times 10^7$ and inserting the values of other constants

$$\frac{Me^2E_0^2}{12\,K\,m^2\,\nu_c^2} \approx 3.87 \times 10^8$$

which shows that this formula is not valid for the radiofrequency field and may be valid in case of microwaves and it is indeed for the microwave frequency that the above expression was deduced.

From the theory of the positive column and assuming Maxwell Boltzman distribution law, Von Engel (1955) deduced that

$$\frac{e^{\chi}}{\chi^{1/2}} = 1.2 \times 10^7 (C\,P\,R)^2$$

where C is a constant $= \left(\frac{a\,V_i^{1/2}}{K^+P}\right)$ and $\chi = \frac{e\,V_i}{K\,T_e}$, R = radius of the tube, P the pressure, V_i the ionization potential of the gas and K^+ the mobility of the positive ions and 'a' is the efficiency of ionization, the values of 'a' for different gases have been given by Von Engel

Hence

$$\frac{e^{\chi}}{\chi^{1/2}} = \frac{1.2 \times 10^7}{K^+}\,a\,V_i^{1/2}R^2P = \alpha P$$

where α is a constant for a particular gas and for a tube of radius R.

then

$$\chi - \frac{1}{2}\log\chi = \log\alpha P$$

$$\frac{d\chi}{dp} = \frac{1}{P\left(1 - \frac{1}{2\chi}\right)}$$

now remembering that

$$\frac{d\chi}{dp} = -\frac{e\,V_i}{K\,T_e^2}\cdot\frac{d\,T_e}{dp}$$

we get $$\frac{d\,T_e}{dp} = \frac{K\,T_e^2/e\,V_i}{P\left[\frac{K\,T_e}{2\,e\,V_i} - 1\right]}$$

In general the values of electron temperature in rare gases is of the order of 10^4 and $K T_e / 2eV_i$ becomes smaller than 1 ; hence $\frac{dT_e}{dP}$ is negative; that is the values of electron temperature diminish with the increase of pressure. The nature of variation is shown in different curves obtained for the six gases. The general variation of T_e with pressure can thus be explained at least qualitatively by assuming that the electrons follow a Maxwellian distribution law though the electrons in rare gases do not actually follow this distribution.

VARIATION OF ELECTRON TEMPERATURE IN MAGNETIC FIELD.

The radiofrequency conductivity of ionised gas has been measured in magnetic field (Gupta and Mandal 1967) as described earlier; the electron temperature has been calculated as before at a particular pressure for different values of magnetic field and the variation of T_e with magnetic field has been plotted for different gases in figure (4.20 to 4.25) . The values of electron temperature have been plotted for magnetic field varying from 0 to 550 gauss for helium, neon, argon, hydrogen and 0 to 680 gauss for air carbondioxide and in case of all the six gases, the electron temperature decreases in presence of the field rapidly at first and then slowly. Bickerton and Von Engel (1956) studied the variation of electron temperature in the positivecolumn in helium in presence of a longitudinal magnetic field, who used in their experiment Langmuir probe measurements. The nature of variation of electron temperature is the same as has been obtained in the present investigation. Bickerton and Von Engel attributed the decrease in electron temperature to the influence of magnetic field on the ambipolar diffusion coefficient. This is equivalent to saying that the pressure in presence of magnetic field becomes the equivalent pressure as has been shown by Blevin and Haydon (1958) so that

$$P_H = P\left[1 + C_1 \ H^2/P^2\right]^{1/2} \quad \text{where} \quad C_1 = \left[\frac{e}{m}\frac{L}{v_r}\right]^2$$

where L is the mean free path of the electrons at a pressure of 1 mm. of Hg. and v_r the random velocity. Hence starting from the expression of electron temperature as deduced by Von Engel,

$$\frac{e^{eV_i/KT_e}}{(eV_i/KT_e)^{1/2}} = \frac{1\cdot 2 \times 10^7 \cdot a \cdot V_i^{1/2}}{K^+} R^2 P \qquad \text{...(4.8)}$$

and remembering that the mobility coefficient K^+ of the positive ions is practically unaffected by a magnetic field due to their large mass we get, when the magnetic field is present

$$\frac{e^{eV_i/KT_e}}{(eV_i/KT_e)^{1/2}} = \frac{1\cdot 2 \times 10^7 \cdot a \cdot V_i^{1/2}}{K^+} R^2 P_H \qquad \text{...(4.9).}$$

where T_{eH} is the electron temperature in presence of magnetic field; we get from equation (4.8) and (4.9)

$$\sqrt{\frac{T_{eH}}{T_e}}\ e^{eV_i/K \frac{T_{eH}-T_e}{T_e T_{eH}}} = \frac{P}{P_H} = \frac{1}{\sqrt{1 + C_1 H^2/p^2}}$$

The quantity $eV_i/K = Y$ (say) and let $\beta = \dfrac{1}{\sqrt{1 + C_1 H^2/p^2}}$

and hence $$\frac{T_{eH}}{T_e}\ e^{\frac{2Y(T_{eH}-T_e)}{T_e T_{eH}}} = \beta^2$$

$$\therefore \log \frac{T_{eH}}{T_e} + \frac{2Y(T_{eH}-T_e)}{T_e T_{eH}} = 2\log\beta$$

since from experimental results, $\frac{T_{eH}}{T_e} < 1$ and for values of T_{eH} not much different from T_e,

$$\frac{T_{eH} - T_e}{T_e} + 2Y \frac{T_{eH} - T_e}{T_e^2} = 2 \log \beta$$

$$\text{or} \quad T_{eH} - T_e = \frac{2 T_e^2 \log \beta}{T_e + 2 eV_i/K}$$

$$T_{eH} = T_e + \frac{2 T_e^2 \log \left(\frac{1}{\sqrt{1 + C_1 H^2/P^2}} \right)}{T_e + 2 eV_i/K} \qquad \ldots(4.10).$$

The values of the terms appearing in equation (4.10) have been calculated as follows. In calculating the values of $C_1 = \left(\frac{e}{m} \frac{L}{v_r} \right)^2$ the random velocity has been obtained from the relation $v_r = \nu_c \lambda_c$ for maximum value of conductivity and L is the mean free path of the electrons at a pressure of 1 mm. of Hg. which has been obtained from the relation $L = 1/A_0$ where A_0 is the constant appearing in the Townsend's equation and whose values are given by Von Engel (1955) for different gases eV_i/K has been calculated from the known values of the ionization potential and the values have been entered in Table (4.2).

TABLE - 4.2

Gas	C_1	$2eV_i/K$
Helium	5.035×10^{-3}	5.74×10^5
Neon	3.765×10^{-3}	5.035×10^5
Argon	2.76×10^{-3}	3.713×10^5
Air	7.1×10^{-4}	5.7×10^5
Carbondioxide	9.3×10^{-4}	3.24×10^5
Hydrogen	3.8×10^{-3}	3.642×10^5

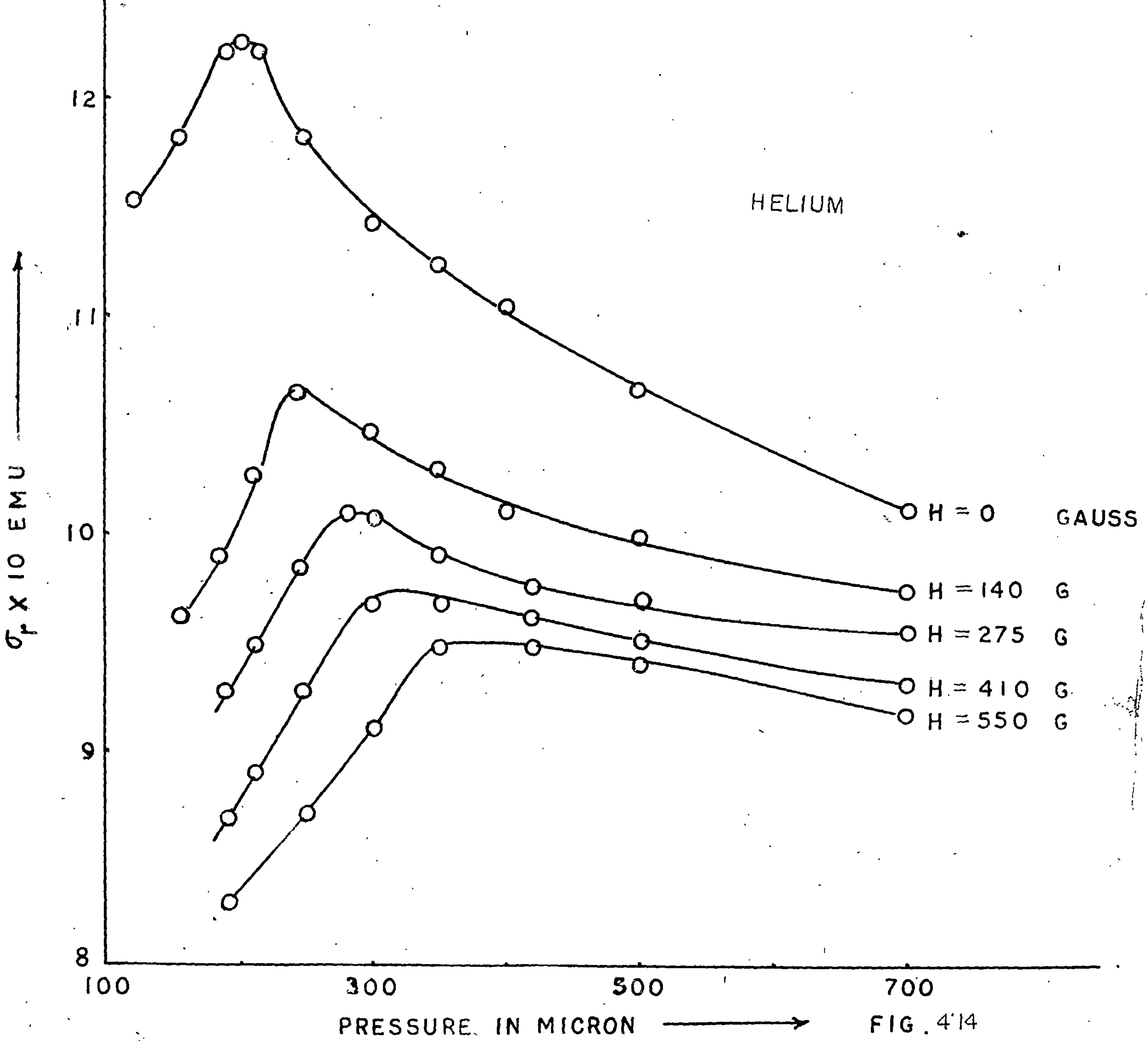
The theoretical values of electron temperature calculated from the above equation and for different values of the magnetic field have been plotted in figure (4.20 to 4.25) side by side with the experimental curves. The general nature of the curve is almost of the some form as the experimental curve and the quantitative disagreement may be ascribed to the uncertainty in the values of C_1, and the random velocity which has been assumed in calculating is actually found to change with magnetic field. The quantitative agreement is satisfactory specially for low values of magnetic field below 100 gauss in the case of all the six gases and this is due to the fact that the equivalent pressure expression from which this formula has been deduced is valid for low magnetic fields only as has also been observed earlier.

VARIATION OF RADIOFREQUENCY CONDUCTIVITY WITH PRESSURE AND MAGNETIC FIELD.

The variation of radiofrequency conductivity against pressure has been plotted in case of helium, neon, argon, air, carbondioxide and hydrogen for different values of the magnetic field in fig. (4.14 to 4.19); also the conductivity pressure curve without magnetic field has been plotted for comparison. It is observed that the value of σ_r is smaller when magnetic field is present than that without field for all values of pressure and the pressure at which the conductivity becomes a maximum always shifts to higher pressure when the magnetic field is increased. That the real part of r.f. conductivity will be smaller in presence of magnetic field than when the field is absent is evident from the following considerations; we have

$$\sigma_r = \frac{ne^2}{m} \frac{\nu_c}{\nu_c^2 + \omega^2}$$

$$\sigma_{rH} = \frac{ne^2}{m} \frac{\nu_c(\nu_c^2 + \omega^2 + \omega_b^2)}{(\nu_c^2 + \omega^2 + \omega_b^2)^2 - 4\omega\omega_b^2}$$



HELIUM
12
11
10
9
8
$\sigma_r \times 10^{14}$ EMU
H = 0 GAUSS
H = 140 G
H = 275 G
H = 410 G
H = 550 G
100
300
500
700
PRESSURE IN MICRON

FIG. 4.14

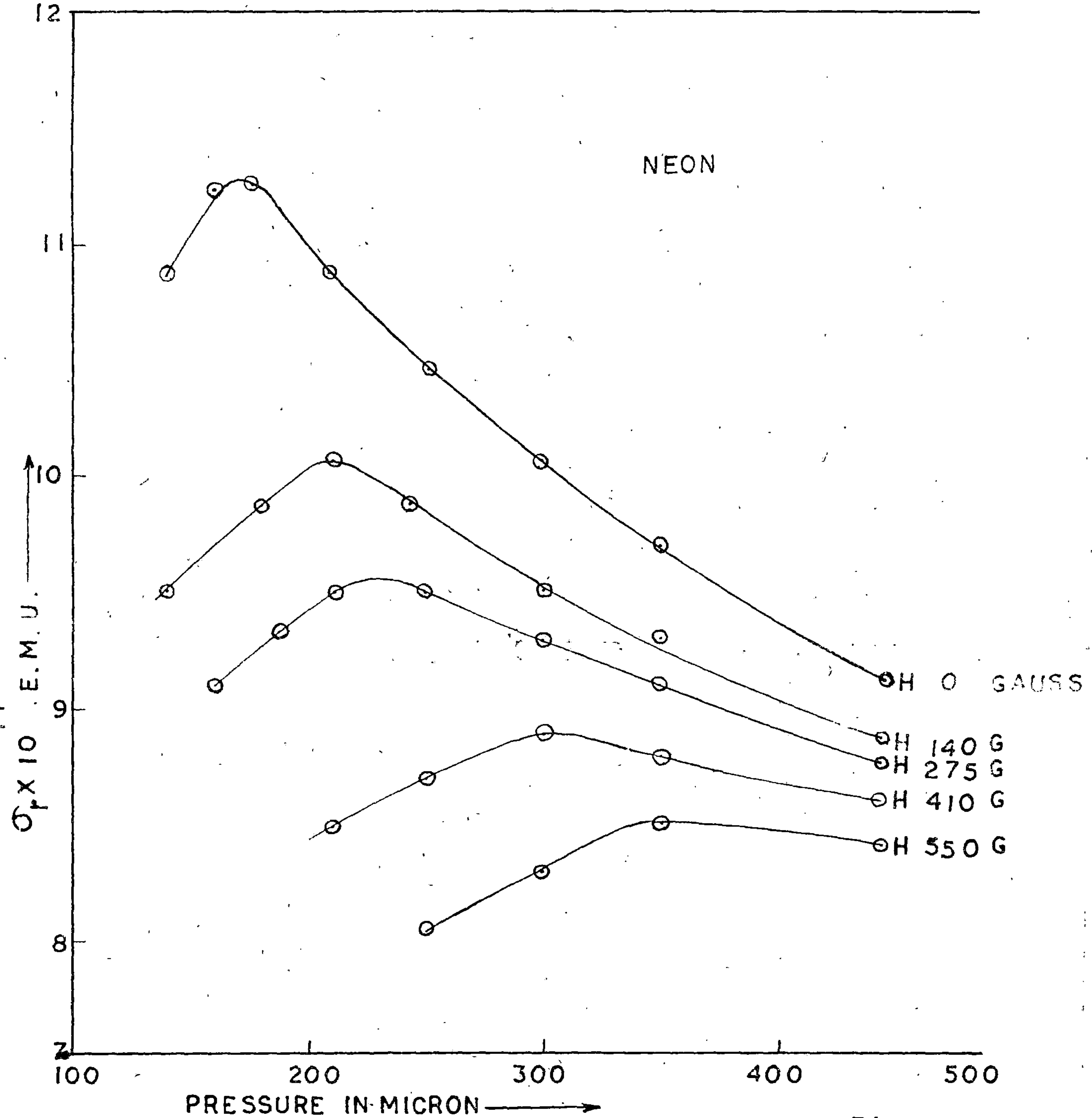

NEON
12
11
10
9
8
7
100
200
300
400
500
PRESSURE IN MICRON
$\sigma_p \times 10^{14}$ E.M.U.
H O GAUSS
H 140 G
H 275 G
H 410 G
H 550 G

FIG. 4·15

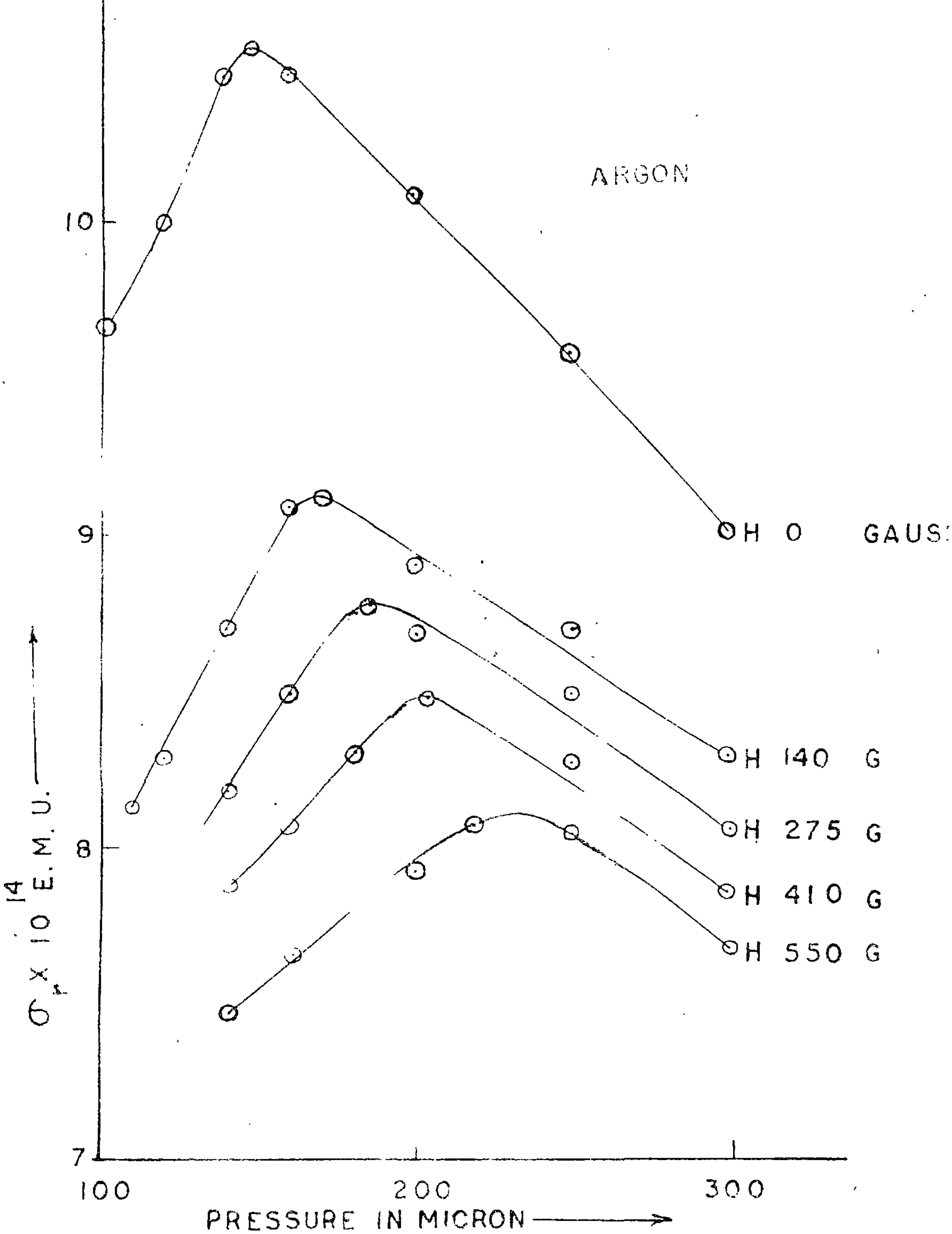

ARGON
10
9
8
7
$\sigma_r \times 10^{14}$ E. M. U.
H 0 GAUSS
H 140 G
H 275 G
H 410 G
H 550 G
100
200
300
PRESSURE IN MICRON

FIG. 4·10

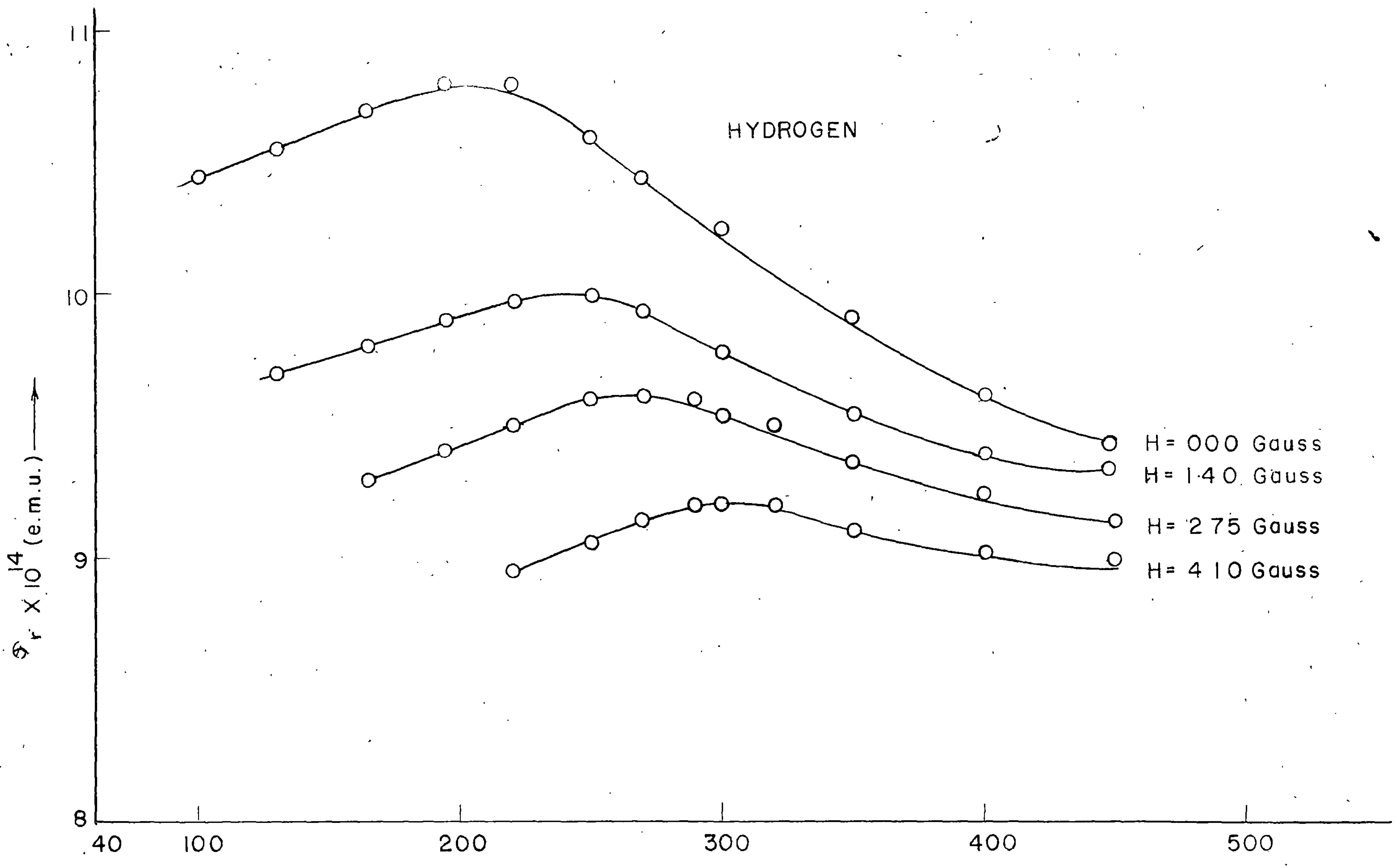
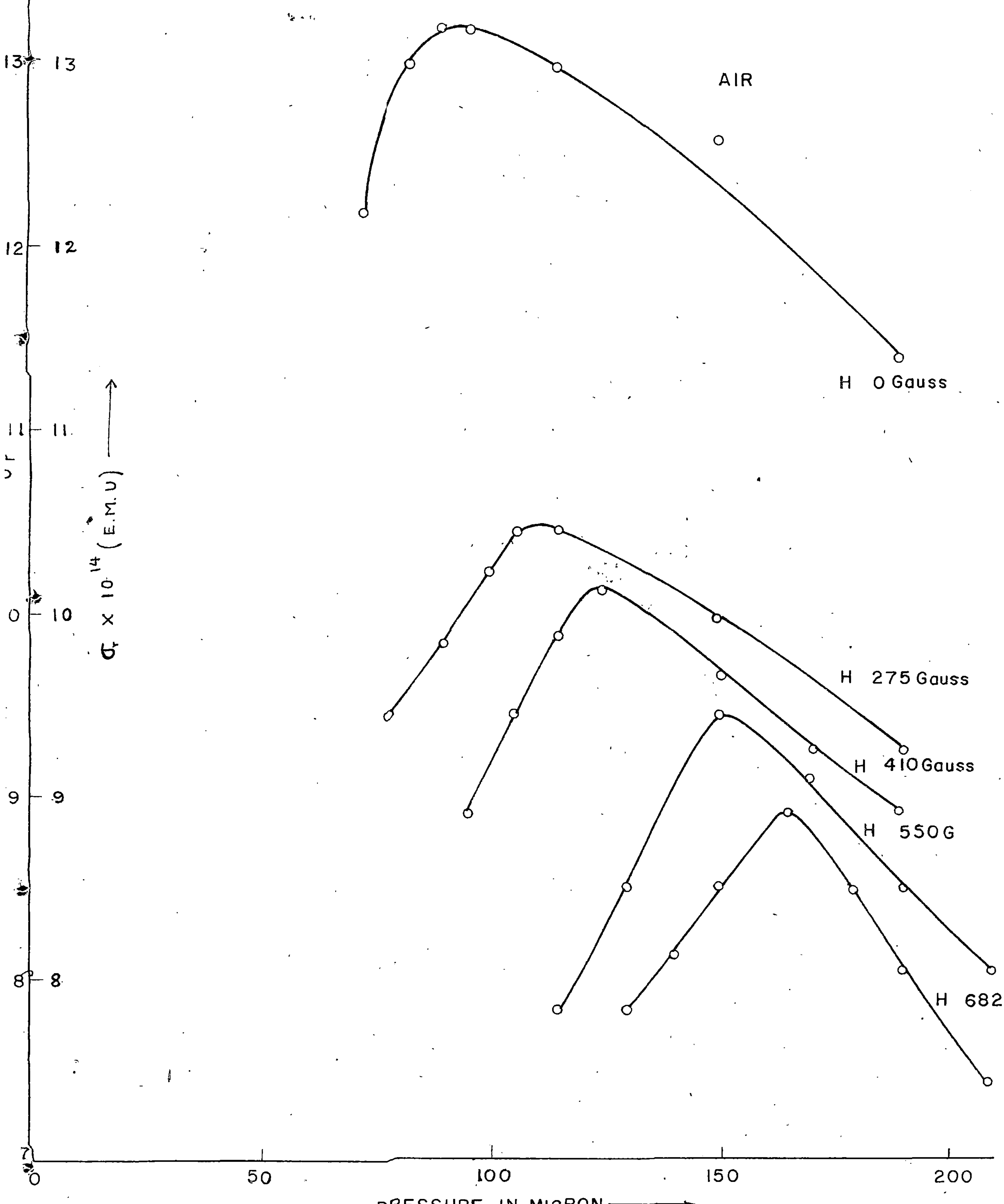

HYDROGEN
H = 000 Gauss
H = 1·40 Gauss
H = 2 75 Gauss
H = 4 10 Gauss
$\sigma_r \times 10^{14}$ (e.m.u.)
Pressure in Micron
11
10
9
8
40
100
200
300
400
500

Fig- 4·17



AIR
H 0 Gauss
H 275 Gauss
H 410 Gauss
H 550 G
H 682
$\sigma_r \times 10^{14}$ (E.M.U)
13
12
11
10
9
8
7
0
50
100
150
200
PRESSURE IN MICRON

Fig — 418

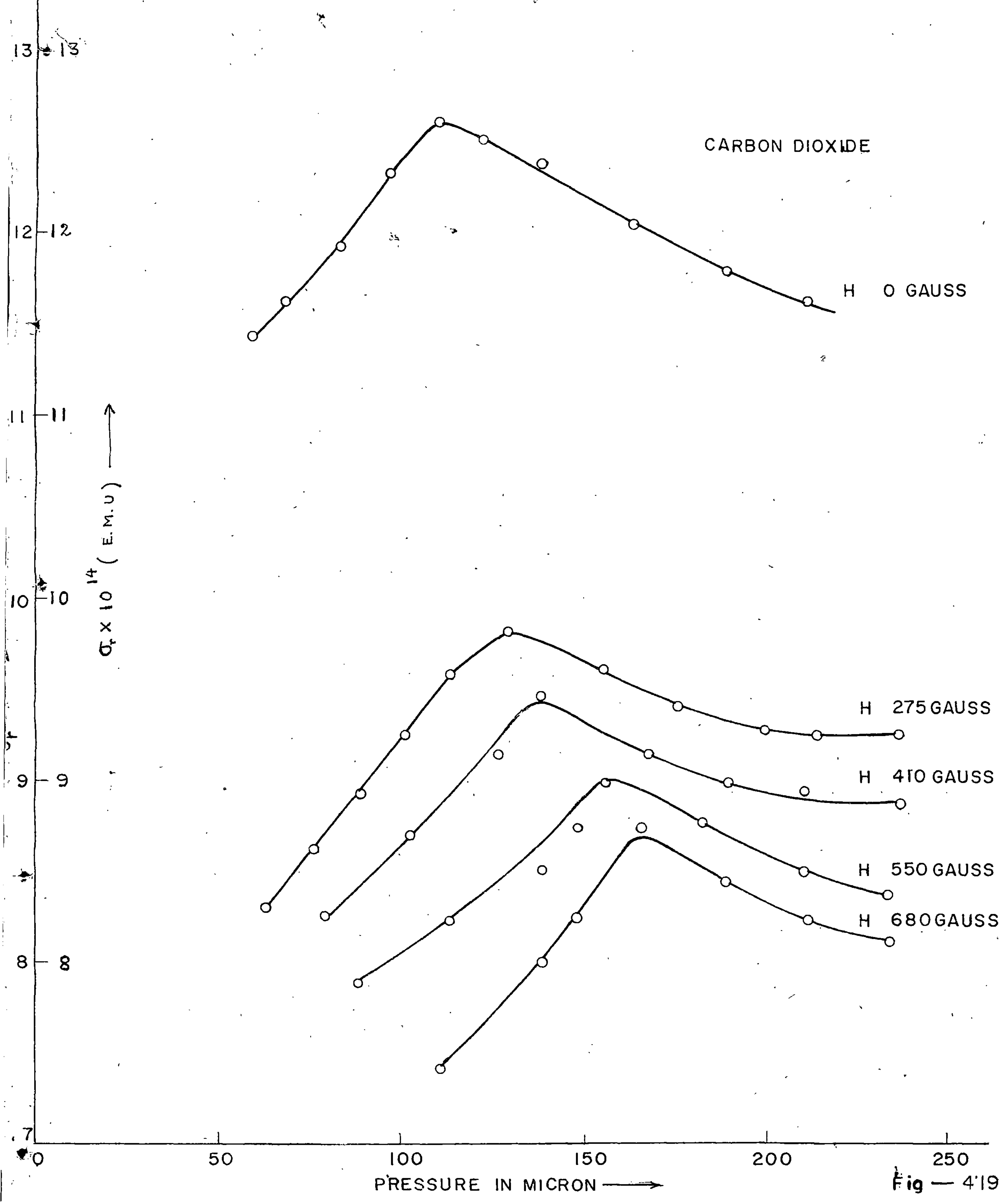
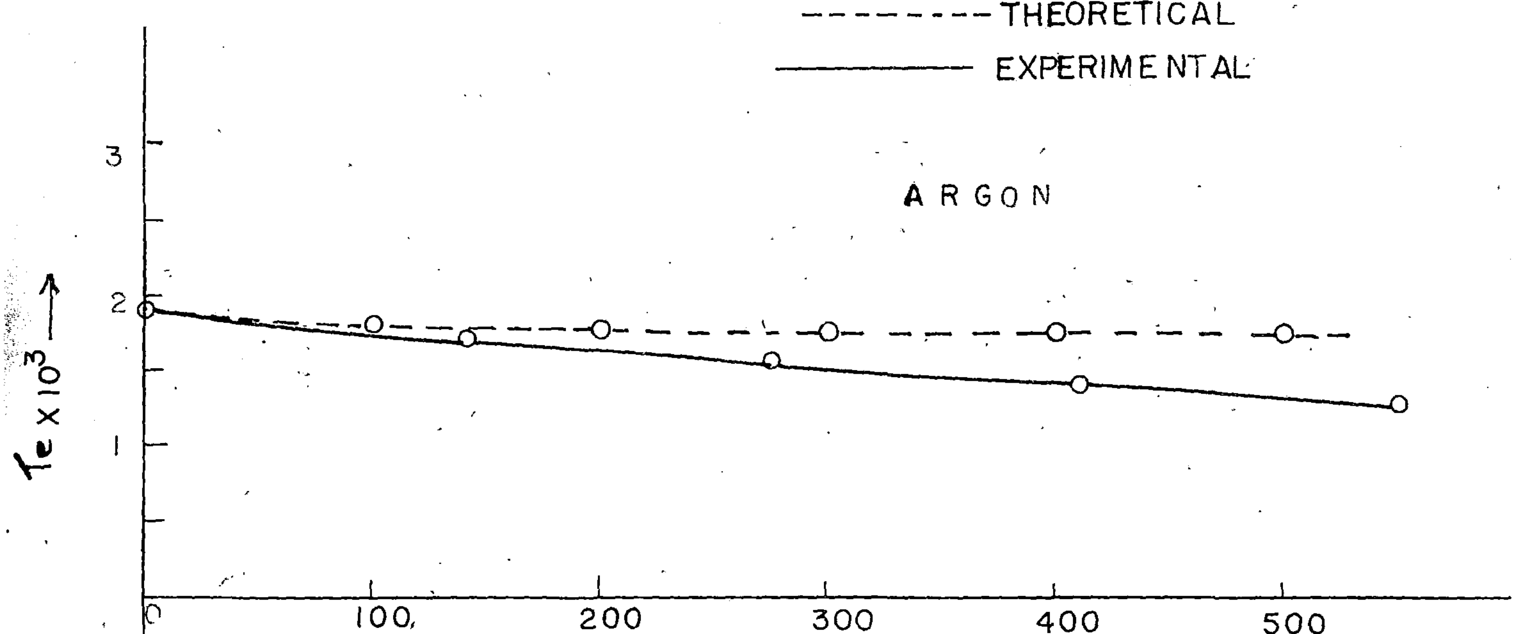

CARBON DIOXIDE
H 0 GAUSS
H 275 GAUSS
H 410 GAUSS
H 550 GAUSS
H 680 GAUSS
$\sigma_r \times 10^{14}$ (E.M.U)
PRESSURE IN MICRON
0
50
100
150
200
250
7
8
9
10
11
12
13

Fig — 4·19



Fig— 4.22

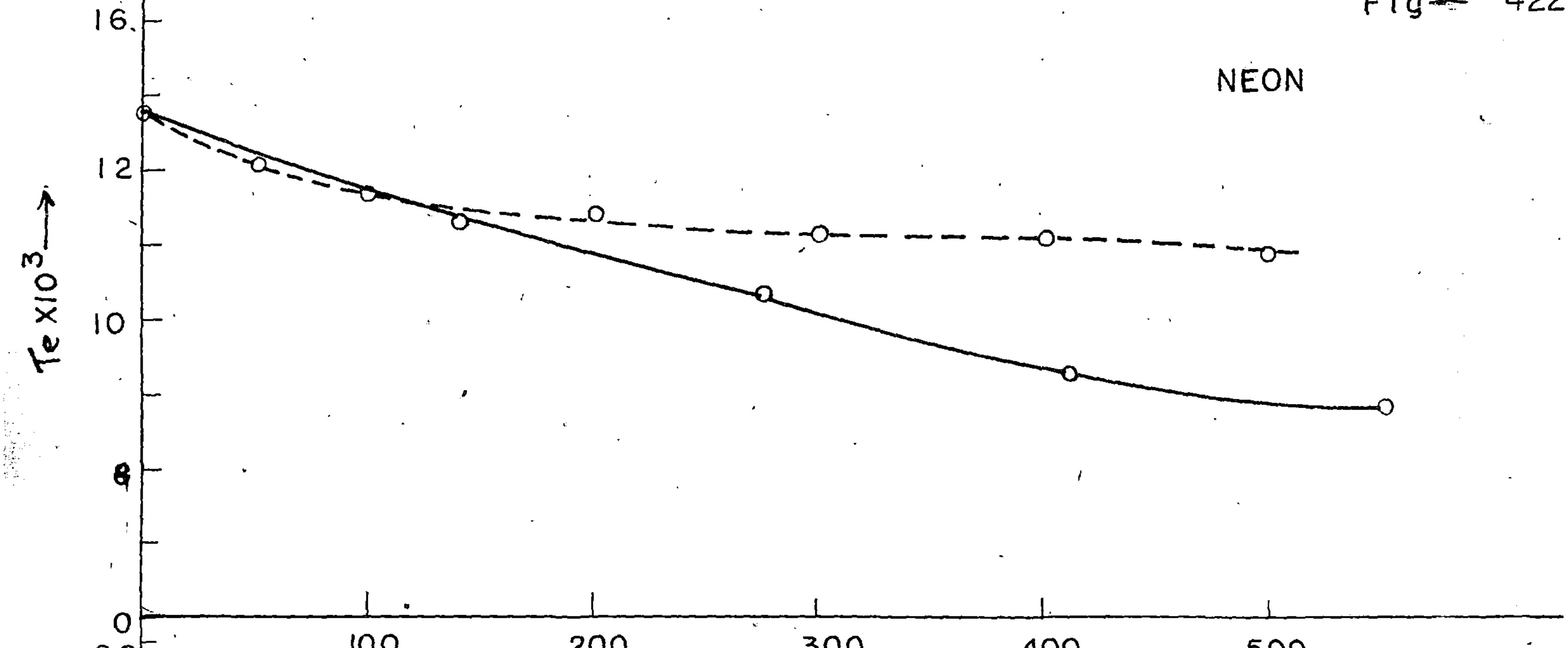
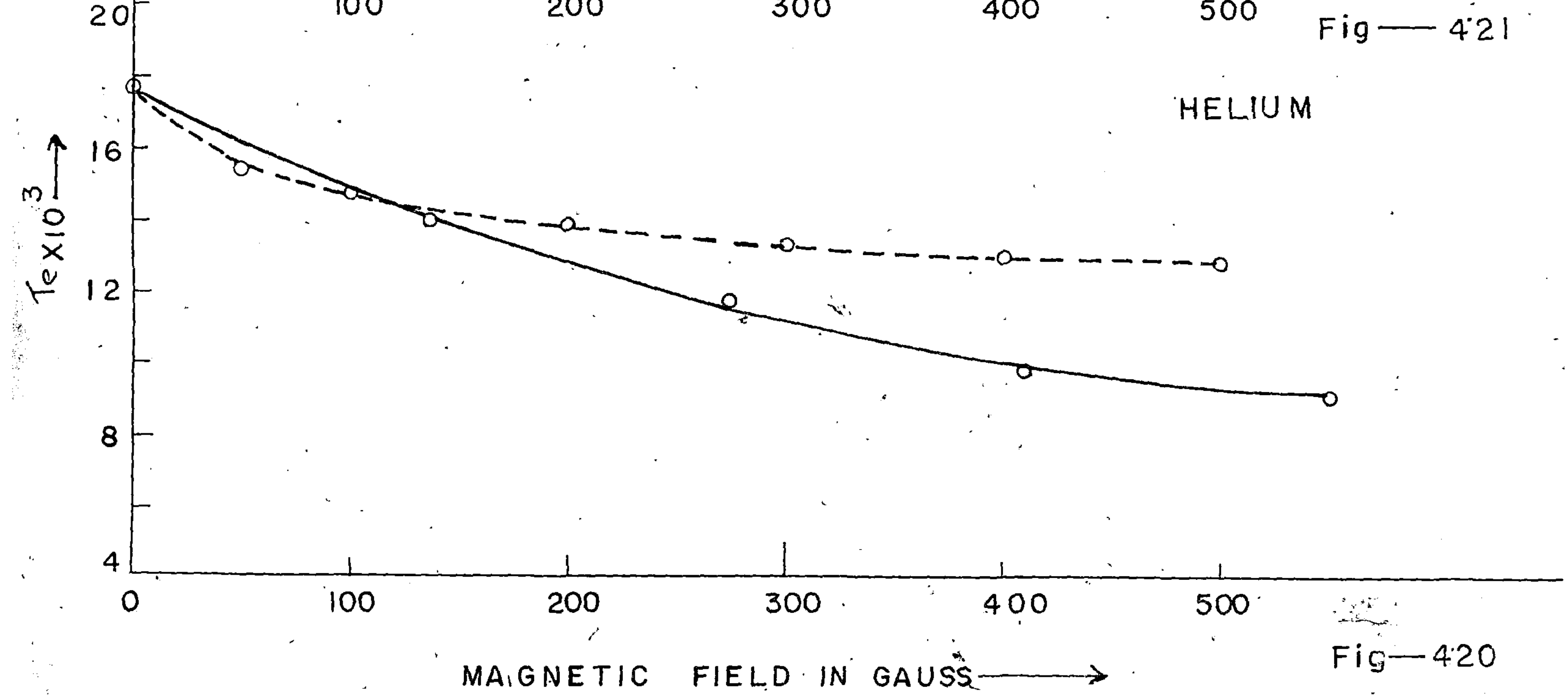


Fig — 4.21



Fig— 4.20

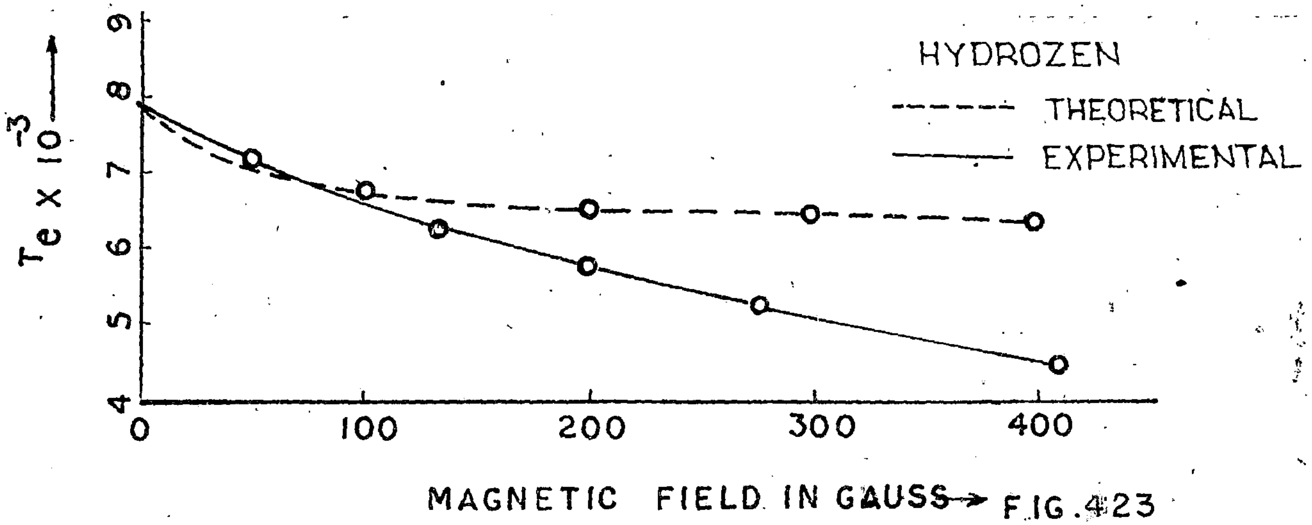

HYDROZEN
THEORETICAL
EXPERIMENTAL
$T_e \times 10^{-3}$
9
8
7
6
5
4
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

FIG. 4.23

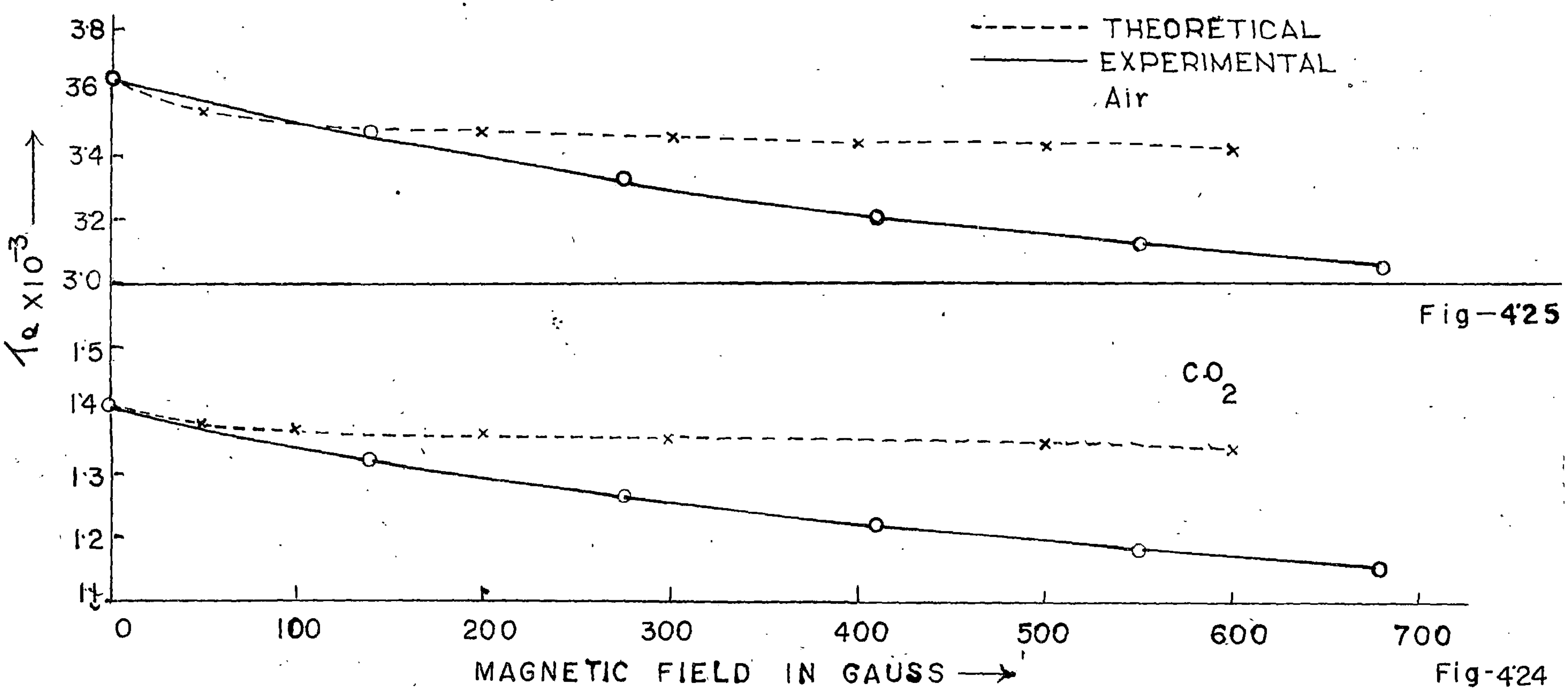


Fig-4·25

Fig-4·24

so that when the magnetic field employed is of the order of 200 gauss we get

$$\omega = 3.52 \times 10^{9} \text{ radians}$$

and for $H = 300$ gauss

$$\omega = 5.28 \times 10^{9} \text{ radians}$$

whereas the frequency of the applied field is of the order of 10.6×10^{6} cycles/Sec. or 6.658×10^{7} radians; we can therefore neglect ω in comparison to ω_b and hence obtain

$$\sigma_{rH} = \frac{ne^2}{m} \frac{\nu_c(\nu_c^2 + \omega_b^2)}{(\nu_c^2 + \omega_b^2)^2 - 4\omega^2\omega_b^2}$$

then

$$\sigma / \sigma_{rH} = \frac{(\nu_c^2 + \omega_b^2)^2 - 4\omega^2\omega_b^2}{(\nu_c^2 + \omega_b^2)(\nu_c^2 + \omega^2)}$$

and neglecting $4\omega^2\omega_b^2$ in comparison to $(\omega_b^2 + \nu_c^2)^2$

we get

$$\sigma / \sigma_{rH} = \frac{1 + \omega_b^2/\nu_c^2}{1 + \omega^2/\nu_c^2}$$

and since $\omega_b >> \omega$; σ/σ_{rH} will be greater than unity as is actually found to be the case in the range of pressure investigated. Considering from the physical point of view it is seen that due to the presence of magnetic field the *effective mean free path is shortened* and now there is a greater number of collisions which results in a net reduction in the number of drifting electrons contributing to the conductivity current and hence the conductivity decreases. However, in the discussion which follows it will be assumed that the number of electrons per unit volume is the same in presence of magnetic field as in its absence, because it is clearly observed in the course of experiment as well as from theoretical considerations that there is a gradation of concentrations of

TABLE- 4.3.

Gas	Magnetic field in gauss	$(\sigma_r)_{max}$ $\times 10^{14}$ e.m.u	Random velocity calculated from $\nu_c = \upsilon_r/\lambda_e$ $\upsilon_r \times 10^{-8}$ cm/sec	$(P_H)_{max}$ in micron from experiment	$(P_H)_{max}$ in micron from equation (4.11)	$(P_H)_{max}$ in micron from equation (4.12)
	0	12.275	8.28	200		
	140	10.675	7.34	242	230.0	259
He	275	10.100	6.863	282	243.1	295
	410	9. 725	6.166	320	252.4	338.4
	550	9. 500	5.82	352	258.4	343.2
	0	11.3	7.17	172.5		
	140	10.1	6.36	210.0	193.1	217.3
Ne	275	9.55	5.77	250.0	204.1	254. 1
	410	8.90	4.95	300.0	219.1	317.4
	550	8.51	4.59	350.0	229.4	358.1
	0	10.56	2.704	148		
	140	9.13	2.56	168	171.2	174.5
A	275	8.80	2.43	184	177.6	197.6
	410	8.53	2.33	202	183.2	212.3
	550	8.20	2.18	222	190.6	243.1
	0	10.80	5.48	210		
	140	10.00	4.917	245	227	253
H_2	275	9.61	4.523	270	236	285
	410	9.20	4.17	305	246	325
	0	12.6	2.904	108		
	275	9.85	2.52	125	140	162
CO_2	410	9.45	2.25	140	146	183
	550	9.00	2.026	155	154	210
	680	8.725	1.938	162	157.9	224
	0	13.175	4.50	92		
	275	10.475	3.75	112	115	
air	410	10.125	3.414	123	118	135
	550	9.175	2.80	150	130.02	155
	680	8.923	2.41	170	136	204

electrons in the path of the radiofrequency field but the average number approximately remains the same.

The values of pressure at which the conductivity becomes maximum in all the case of helium, neon, argon, air, corbondioxide and hydrogen have been obtained from the curve of fig. (4.14 to 4.19) and entered in table-(4.3). It is evident that the value of pressure at which the conductivity becomes a maximum shifts to higher values with the application of the magnetic field. To explain this it is observed that since $\omega_b \gg \omega$ for the values of magnetic field employed

$$\sigma_{rH} = \frac{ne^2}{m} \frac{\nu_c}{\nu_c^2 + \omega_b^2}$$

and putting $$\nu_c = \frac{v_r}{\lambda_e} = \frac{v_r P}{L}$$

where L is the mean free path of the electron in the gas at a pressure of 1 mm. of Hg.

Then $$\sigma_{rH} = \frac{ne^2}{m} \frac{L}{v_r} \frac{P}{P^2 + C_1 H^2}$$

where $$C_1 = \left[\frac{e}{m} \frac{L}{v_r}\right]^2$$

and σ_{rH} will be a maximum with respect to P

when $$(P_H)^2_{max} = C_1 H^2$$

where $(P_H)_{max}$ is the pressure at which the conductivity becomes a maximum in presence of magnetic field

then $$(\sigma_{rH})_{max} = \frac{1}{2} \frac{ne^2}{m} \frac{L}{v_r} \frac{1}{(P_H)_{max}}$$

and $$(\sigma_r)_{max} = \frac{1}{2} \frac{ne^2}{m} \frac{L}{v_r} \frac{1}{P_{max}}$$

so that $$(P_H)_{max} = \frac{(\sigma_r)_{max}}{(\sigma_{rH})_{max}} P_{max} \qquad \ldots(4.11).$$

The values of $(\sigma_r)_{max}$ and $(\sigma_{rH})_{max}$ as well as P_{max} can be obtained from experimental data and hence $(P_H)_{max}$ can be calculated. The results calculated from the above expression has been entered in the sixth column of Table (4.3) where P_{max} is the pressure at which the conductivity becomes maximum in absence of magnetic field.

It is thus seen that there is some agreement between the values of $(P_H)_{max}$ calculated and these observed experimentally specially for low values of magnetic field in the case of all the six gases studied and the disagreement is more pronounced for high values of magnetic field. But this formula has to be modified because it has been observed that the electron temperature and hence random velocity becomes a function of the magnetic field. In deducing equation (4.11) it was assumed that $\upsilon_r = \upsilon_{rH}$ but as υ_r varies with magnetic field

$$(\sigma_r)_{max} = \frac{ne^2}{2m} \cdot \frac{L}{\upsilon_r} \cdot \frac{1}{P_{max}}$$

and

$$(\sigma_{rH})_{max} = \frac{ne^2}{2m} \cdot \frac{L}{\upsilon_r} \cdot \frac{1}{(P_H)_{max}}$$

Hence
$$(P_H)_{max} = \frac{\upsilon_r}{\upsilon_{rH}} \cdot \frac{(\sigma_r)_{max}}{(\sigma_{rH})_{max}} \cdot P_{max} \qquad \ldots(4.12).$$

The values of υ_r and υ_{rH} as calculated from the maximum values of conductivity have been entered in column (4) of Table (4.3) for the six gases and the value of $(P_H)_{max}$ as calculated from equation (4.12) have been entered in the last column of Table (4.3). It is clear that when the formula is thus modified it gives very good agreement with the observed experimental results. As has been noted in the previous paper, the range of validity of equivalent pressure is very limited and specially it fails for high values of magnetic field. Further the expression for equivalent pressure was deduced on the assumption that electron distribution is mainly governed by Maxwell Boltzman distribution which holds specially for molecular gases and it is known that electron distribution in rare and other gases is not governed by Maxwell Boltzman law which may account to a certain extent the observed discrepancy.

DIELECTRIC CONSTANT OF PLASMA

It is further observed that besides the above parameters, the dielectric constant of the plasma can also be determined from the measured radiofrequency conductivity of the ionised gas. It is well known that the dielectric constant of plasma is given by

$$\epsilon = 1 - \frac{4\pi n e^2}{m\omega^2}$$

and this treatment neglects the collisions between electrons and ions and neutral molecules. However when this is taken into consideration ϵ^* the complex dielectric constant is given by

$$\epsilon^* = \epsilon' - j\epsilon''$$

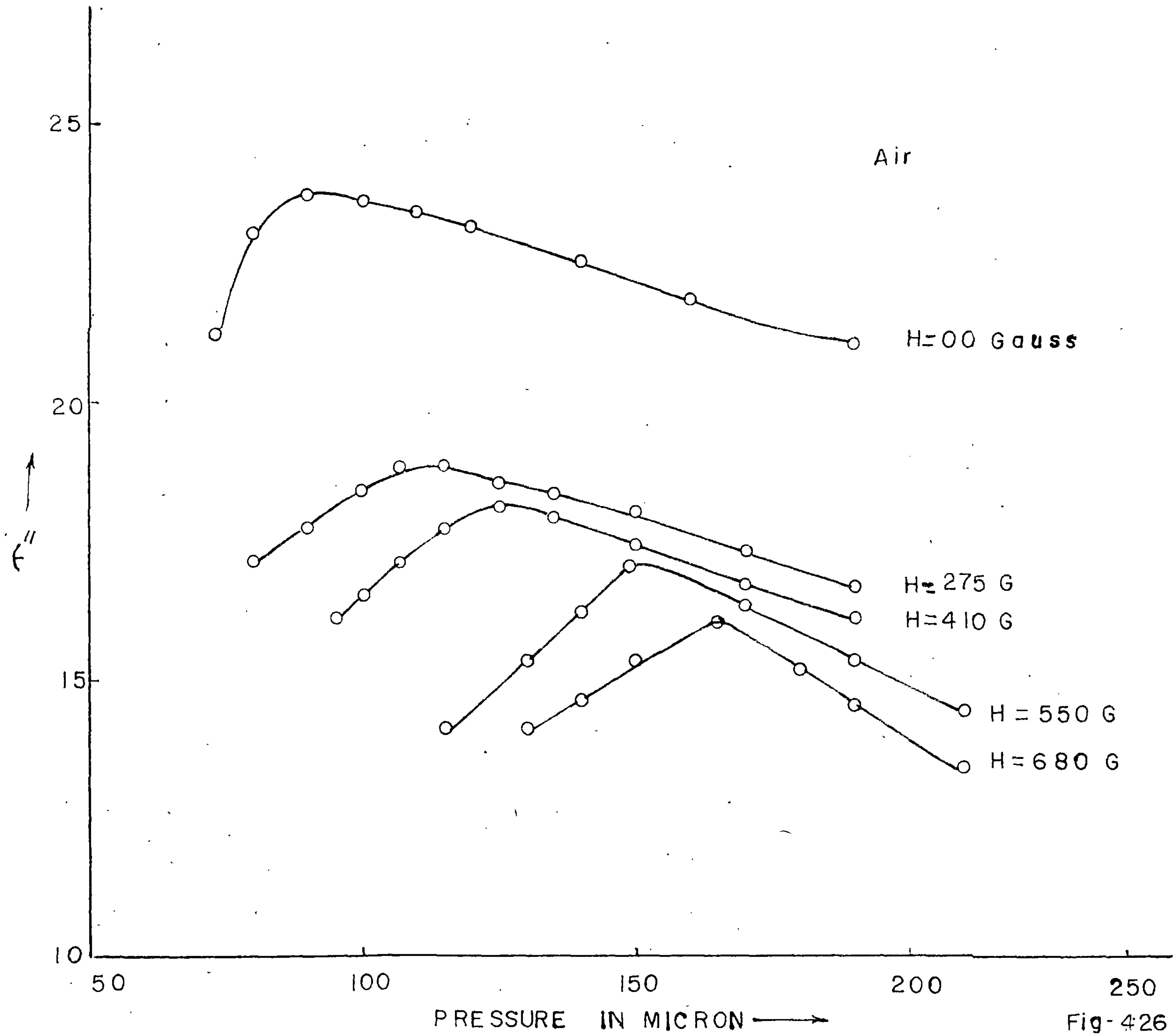
$$\text{where} \quad \epsilon' = 1 - \frac{4\pi n e^2 \omega}{m(\nu_c^2 + \omega^2)\omega} = 1 - \frac{4\pi\sigma_i}{\omega}$$

$$\text{and} \quad \epsilon'' = \frac{4\pi}{\omega}\,\frac{n e^2}{m}\,\frac{\nu_c}{\nu_c^2 + \omega^2}$$

$$= 4\pi\sigma_r/\omega \qquad \ldots(4.13)$$

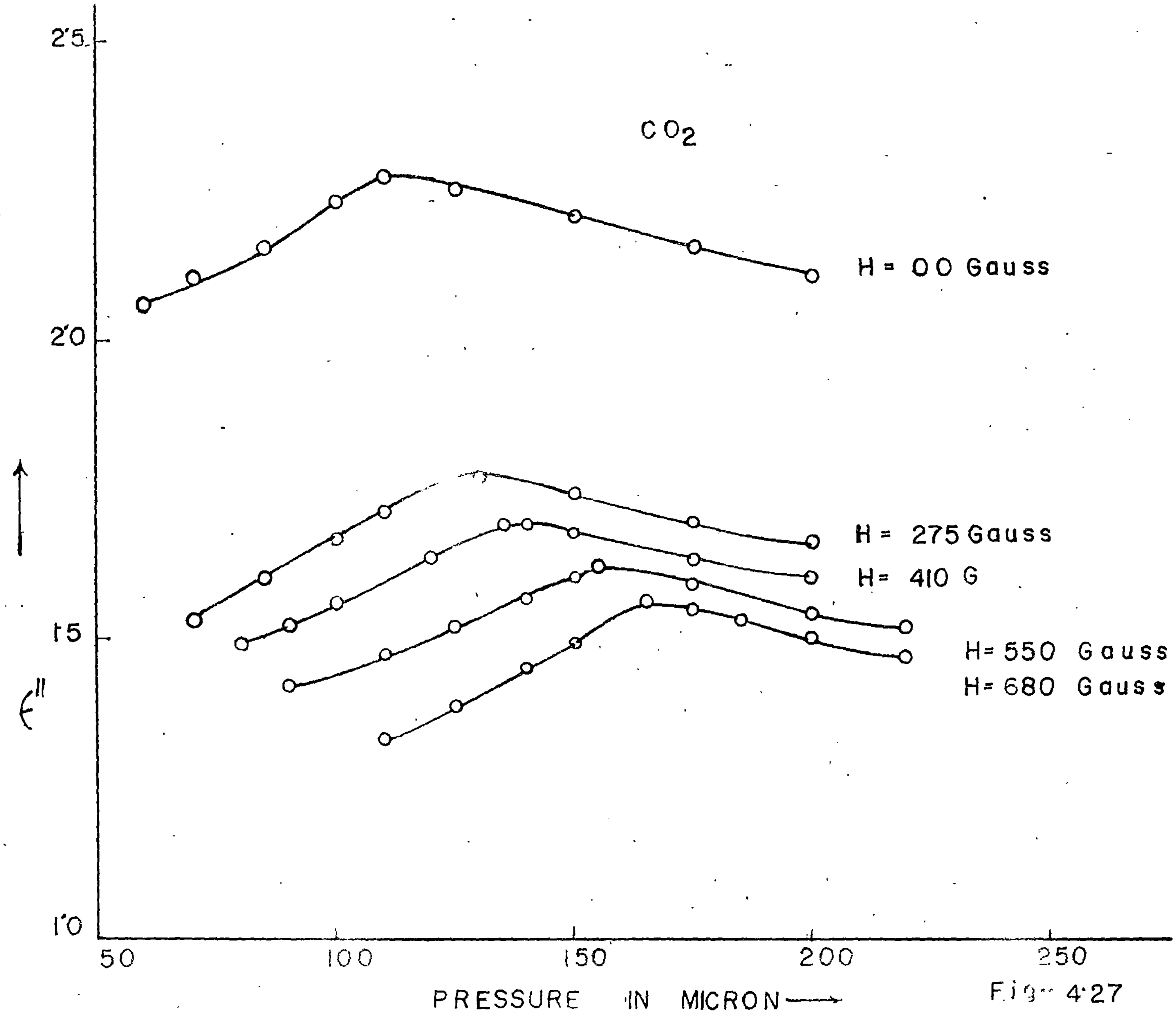
where σ_r and σ_i are the real and imaginery parts of radiofrequency conductivity. The dielectric properties of ionised gases were measured by Gutton and Clement (1927) and Gutton (1930) who used the energiosed plasma to terminate a lecher line. Adler (1949) measured the conductivity of ionised gases in the microwave region and Dutt (1966) has also measured the dielectric properties of the rare gases in the after glow plasma.

The values of σ have been experimentally determined for helium, argon, neon, air, carbondioxide and hydrogen over a pressure range of a few microns to 700μ and in presence of magnetic field varying from 0 to 550 gauss and hence the value of ϵ'' can be calculated from equation (4.13) and its variation with pressure can be studied.



Air
H=00 Gauss
H= 275 G
H=410 G
H = 550 G
H = 680 G
25
20
15
10
50
100
150
200
250
PRESSURE IN MICRON
ε''

Fig-4.26



CO_2
H = 00 Gauss
H = 275 Gauss
H = 410 G
H = 550 Gauss
H = 680 Gauss
2.5
2.0
1.5
1.0
ε''
50
100
150
200
250
PRESSURE IN MICRON

Fig. 4.27

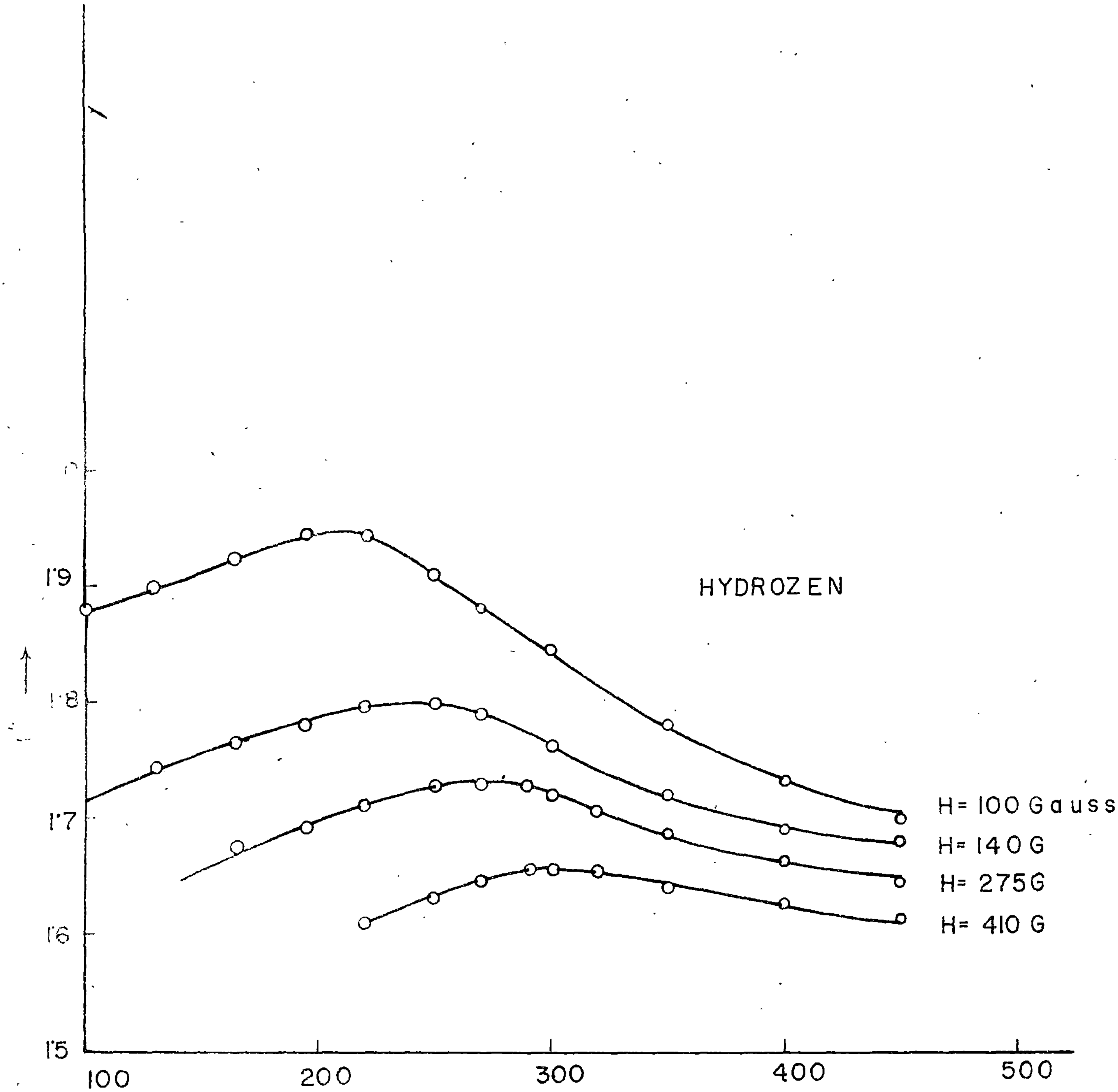

HYDROZEN
H= 100 Gauss
H= 140 G
H= 275 G
H= 410 G
1·9
1·8
1·7
1·6
1·5
100
200
300
400
500
PRESSURE IN MICRON

Fig-4·28

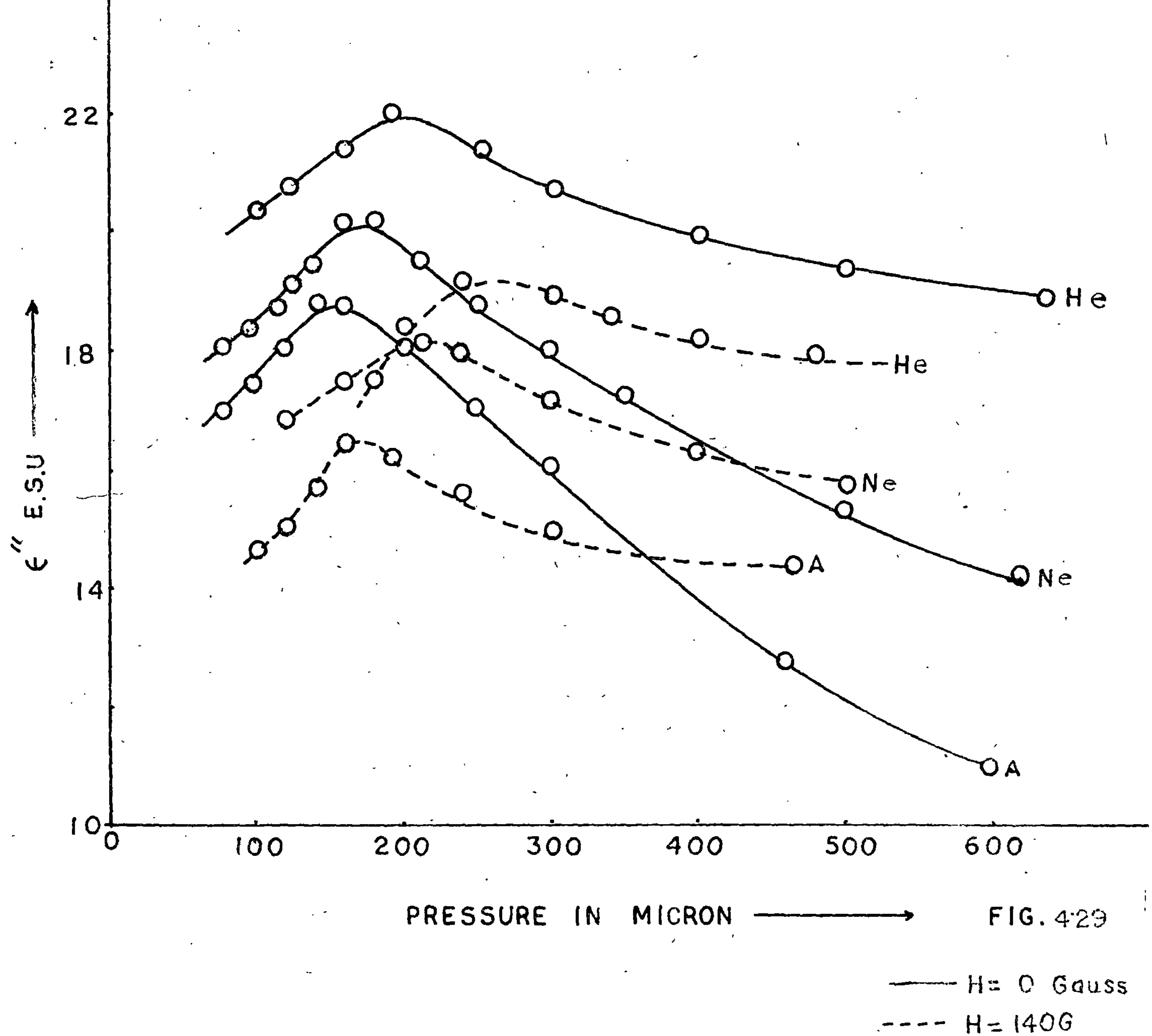

22
18
14
10
ϵ'' E.S.U
0
100
200
300
400
500
600
PRESSURE IN MICRON
He
He
Ne
Ne
A
A
H= 0 Gauss
H= 140G

FIG. 4·29

Such calculations have been made in the case of helium, argon, neon, air, CO_2 and hydrogen for a range of pressure of a few microns to 500 μ from the measured values of σ_r and the variation plotted in figure (4.26 to 4.29) ϵ'' becomes a maximum when σ_r becomes a maximum and this takes place when the collision frequency becomes equal to the applied frequency. Since ϵ'' is the loss factor of the dielectric constant and the loss will evidently become a maximum when σ_r is a maximum; ϵ' can also be calculated if σ_r is measured.

When the plasma is placed in the magnetic field which is at right angles both to the direction of discharge current and the radiofrequency field it has been noted that σ_r diminishes and the pressure at which it becomes a maximum is shifted to higher values of pressure. Similar behaviour is also observed in the case of ϵ'' in the magnetic field. The variation of ϵ'' in the magnetic field for different values of pressure is plotted side by side in fig.

The Debye shielding distance λ_D is given by

$$\lambda_D^2 = \frac{K\,T_e}{4\pi n e^2}$$

and n can be obtained from the relation

$$(\sigma_r)_{max} = \frac{n e^2}{2 m \omega}$$

The evaluation of T_e the electron temperature and its variation in the magnetic field has been studied in case of rare gases and air, carbondioxide and hydrogen here. From the above available data the variation of Debye shielding distance with pressure and magnetic field have been plotted in figure (4.30 to 4.38) respectively. The order of magnitude of λ_D is found to be of the same order as has been calculated by Glasstone and Lovberg (1960) for large electron densities and high electron temperature as are obtained in case of thermo nuclear plasma. Thus from the variation of λ_D with pressure as well as with magnetic field it is observed that the decrease is linear upto 200 gauss in case of helium and upto

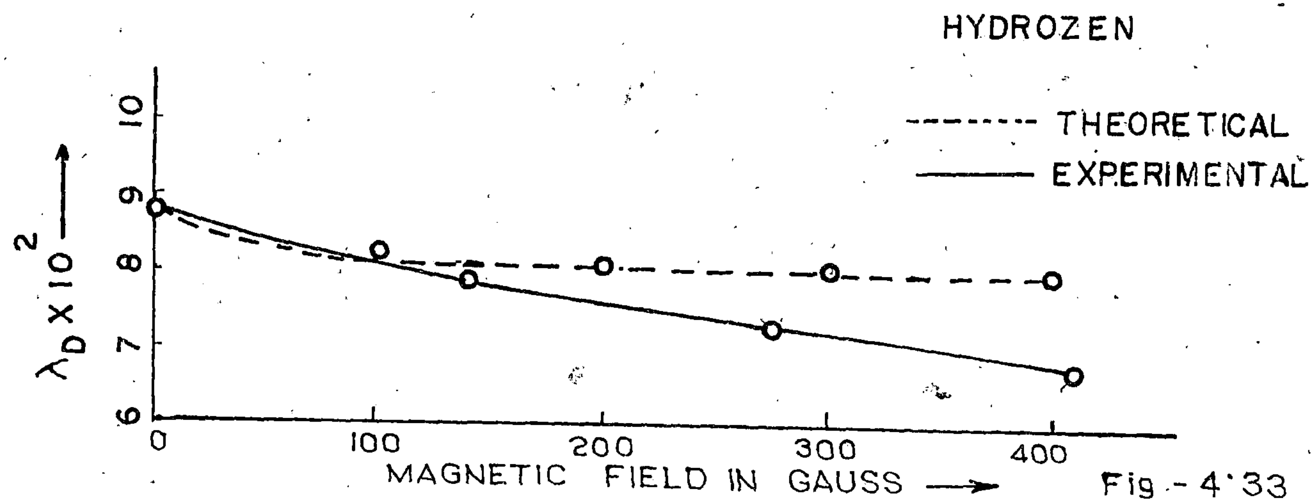

HYDROZEN
THEORETICAL
EXPERIMENTAL
$\lambda_D \times 10^2$
10
9
8
7
6
0
100
200
300
400
MAGNETIC FIELD IN GAUSS

Fig - 4·33

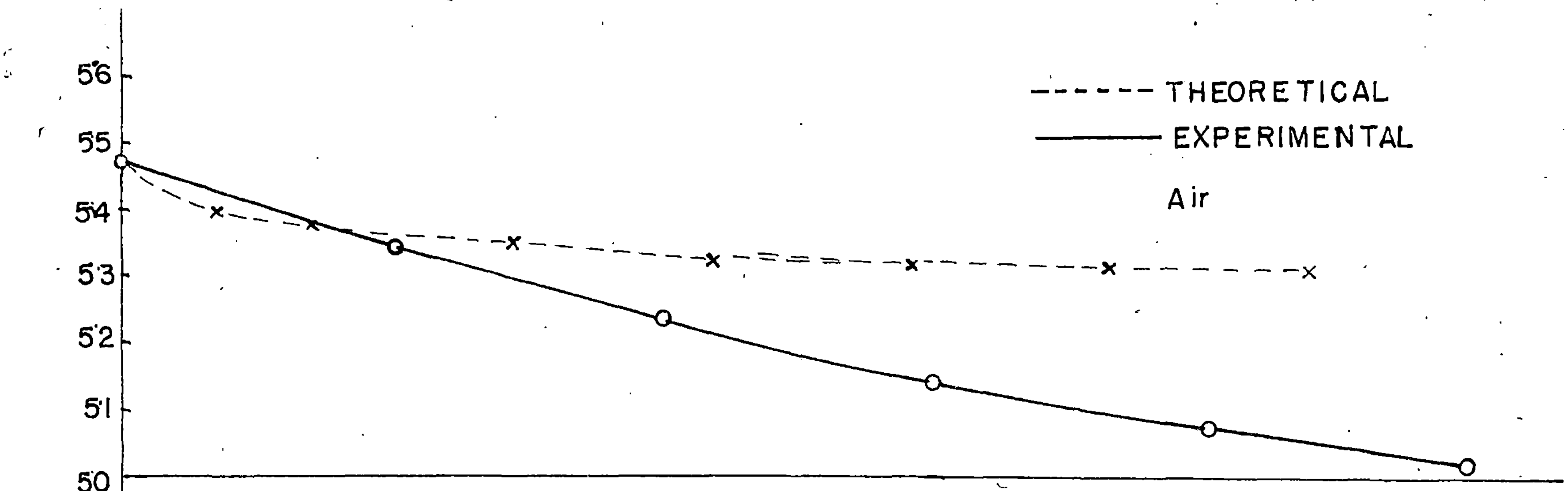


Fig- 4·34

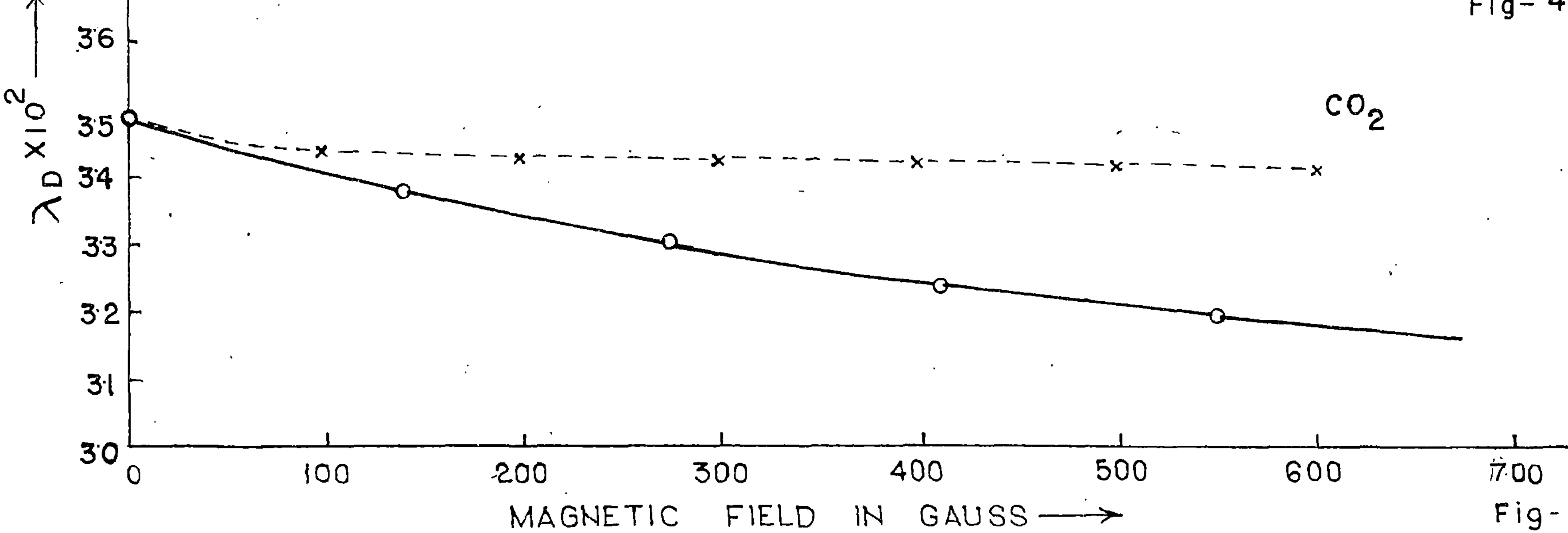
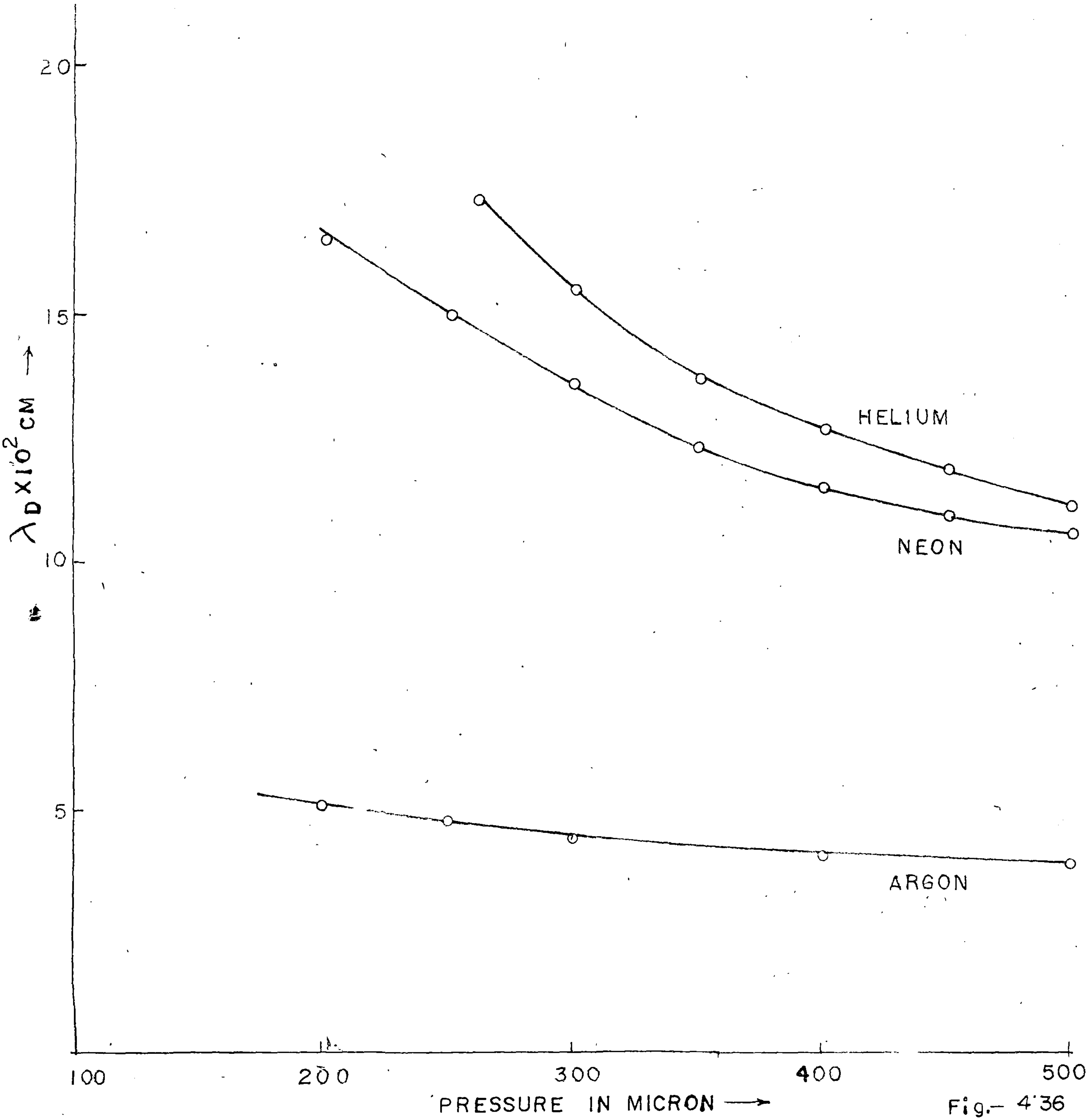
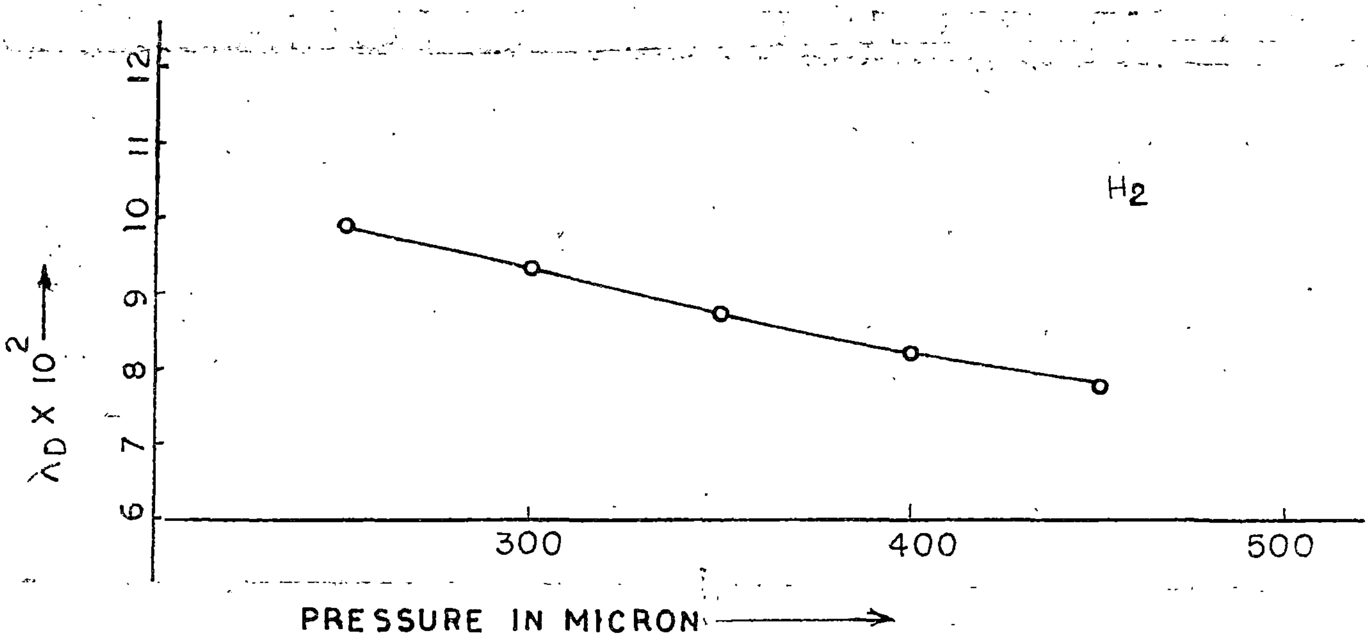


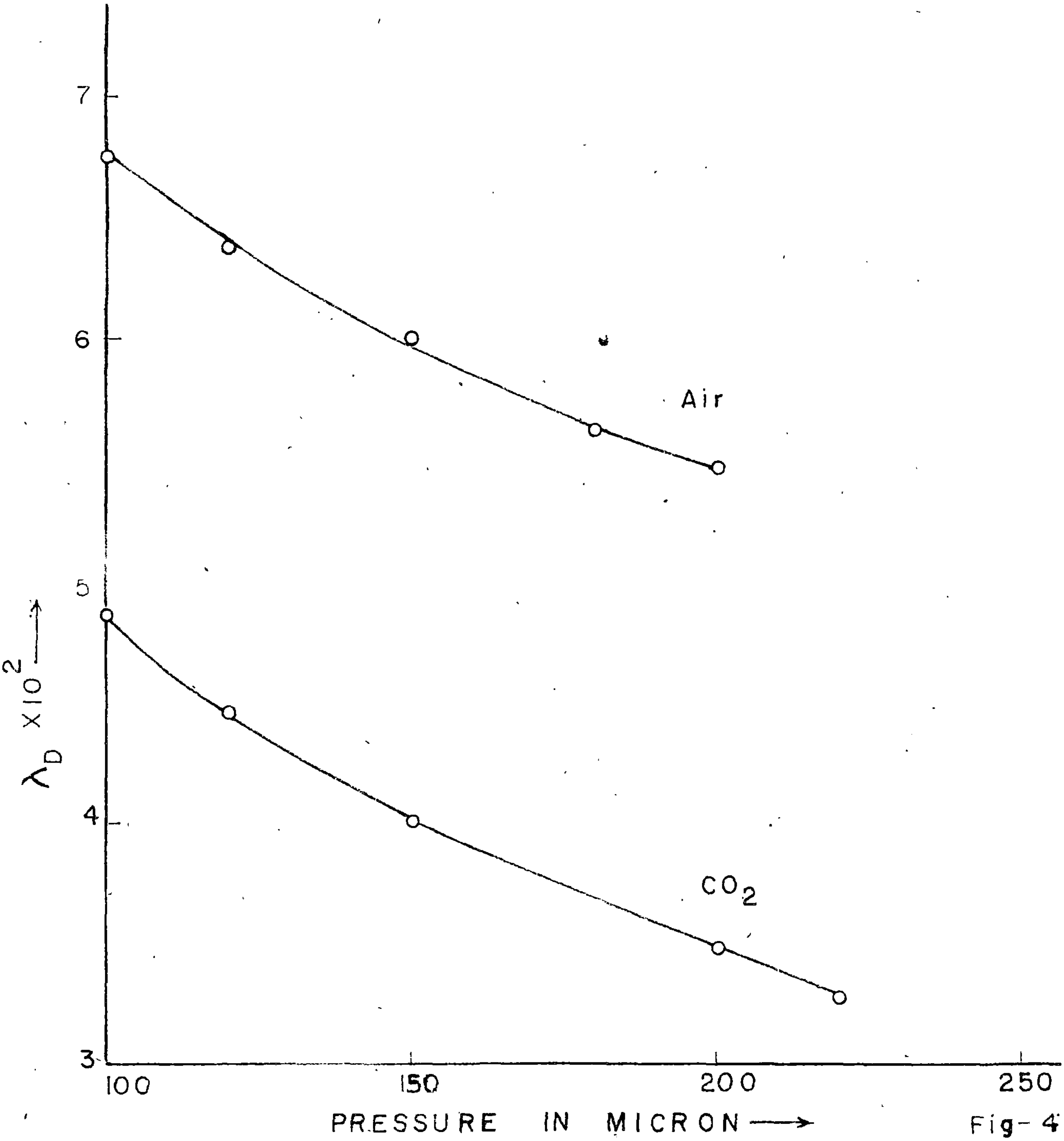
Fig-4·35


$\lambda_D \times 10^2$ CM →
20
15
10
5
HELIUM
NEON
ARGON
100
200
300
400
500
PRESSURE IN MICRON →
Fig.– 4·36



H2
$\lambda_D \times 10^2$
6
7
8
9
10
11
12
300
400
500
PRESSURE IN MICRON

FIG. 4·37



7
6
5
4
3
$\lambda_D \times 10^2 \longrightarrow$
Air
CO_2
100
150
200
250
PRESSURE IN MICRON ⟶

Fig-43

approximately 300 gauss in case of neon and carbondioxide and upto 400 gauss in case of hydrogen and air. And in case of argon the linearity in maintained almost upto 500 gauss; above these respective magnetic fields or pressure their is practically little change of λ_D. A qualitative correlation can be established between the change of Debye length and the mean free path of electrons in these gases. It is noted that the mean free path of electrons in case of He, Ne, A, Air, Co_2 & H_2 can be calculated from Townsend coefficient A_o where $A_o = 1/L$, L being the mean free path of electron at a pressure of 1 mm. of Hg. A_o in case of helium, neon, argon, air, carbondioxide and hydrogen being 3, 4, 14, 15, 20 & 5 respectively (Von Engel 1955) and hence the mean free path at a pressure of say 250μ is 1.33 cm., 1.0 cm, .286 cm, .267 cm, .20 cm and .80 cm. respectively for the six gases. The Debye shielding distance is much smaller than the mean free path at this pressure and shows a decrease with increase of pressure, but at higher pressure when the mean free path becomes comparable to λ_D the change becomes very small. The concept of equivalent pressure (Blevin & Haydon 1958) shows that the equivalent pressure increases with magnetic field and hence the change of λ_D with magnetic field can be explained on the same basis as that due to change of pressure.

It can thus be concluded from the above discussion that it is possible from the measurements of radiofrequency conductivity to evaluate the various parameters of plasma and also to study the variation of these parameters with pressure and externally applied magnetic field. These studies further throw considerable light into the processes operation in the discharge.

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RADIO-FREQUENCY CONDUCTIVITY OF IONIZED GASES IN MAGNETIC FIELD

By

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RADIO-FREQUENCY CONDUCTIVITY OF IONIZED GASES IN MAGNETIC FIELD

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(*Received July* 15, 1966 ; *Resubmitted January* 21, 1967)

ABSTRACT. The radio-frequency conductivity of ionized gases (air and Carbondioxide) has been measured within a pressure range of a few microns of Hg to .3 mm of Hg in presence of a magnetic field varying from 0 to 700 Gauss, and a frequency of 10.6 Mc/sec, the discharge being excited by a transformer. It has been observed that conductivity decreases in presence of magnetic field for all values of pressure and the pressure at which the conductivity becomes a maximum increases with the increase of magnetic field. The results can be explained fairly well by an extension of the theory put forward by Gilardini (1959) and the quantitative agreement is also satisfectory. The introduction of the effect of equivalent pressure generally gives results in wide divergence with experimental results and hence it is concluded that for values of (H/P) employed in this case, the equivalent pressure concept does not hold. The reasons for the failure of equivalent pressure expression in this case have been discussed.

INTRODUCTION

In a previous paper (Sen and Ghosh, 1966) a method has been described to measure the radio-frequency conductivity of ionised gases and a study has been made regarding the interaction of radio-frequency waves with ionised gases. Since the presence of a magnetic field changes the various characteristics of a discharge, it is natural to suppose that the radio-frequency conductivity of an ionized gas will also change in presence of a magnetic field. Conductivity of ionized gases such as air, nitrogen and hydrogen in a magnetic field was measured by Ionescu and Mihul (1932) for pressure greater than 10^{-3} mm of Hg who found that maxima other than those due to free electrons could be obtained. With very intense fields, only the vibration due to free electrons remained, the others disappearing and the values of the magnetic field giving maximum conductivity varied with pressure. A theory regarding the variation of radio-frequency conductivity with magnetic field was proposed by Appleton and Boohariwala (1935) who showed that the real part of radio-frequency conductivity in a magnetic field is given by

$$\sigma_{rH} = \frac{ne^2}{m} \cdot \frac{\nu_c(\omega^2+\omega_b{}^2+\nu_c{}^2)}{(\omega^2+\omega_b{}^2+\nu_e{}^2)^2-4\omega^2\omega_b{}^2} . \quad \ldots \quad (1)$$

n is the number of electrons per unit volume and ν_c the collision frequency, ω is the angular frequency of the applied field and $\omega_b = \dfrac{eH}{m}$; from graphical analysis, it was shown by the authors that the value of ν_e for which the conductivity becomes a maximum is obtained when $\nu_c = 0$ which is anomalous and further the experimental results obtained by the authors were not supported by the theory developed; but it was conclusively shown that the magnetic field has a marked influence on the pressure at which the conductivity becomes a maximum and the value of the conductivity changes when the magnetic field is applied. A general theory regarding the variation of radio-frequency conductivity of ionized gases and its variation with pressure and the magnetic field has been worked out by Gilardini (1959) who derived the expression for the conductivity of an ionized gas under the following assumptions:

(a) when the distribution function is predominently spherically symmetrical in velocity space but not necessary Maxwellian.

(b) when the electron collison frequency is an arbitrary function of electron velocity. The value of the complex conductivity is given by

$$\sigma = \frac{e^2 n}{m} \cdot \frac{1}{\nu_e + j\omega}$$

In presence of magnetic field he has defined two conductivities; a conductivity σ_c for the right-handed polarization and a conductivity σ_0 for the left-handed polarization where

$$\sigma_c = \frac{e^2 n}{m} \left[\frac{1}{\nu_c + j(\omega - \omega_b)} \right].$$

and $$\sigma_0 = \frac{e^2 n}{m} \left[\frac{1}{\nu_c + j(\omega + \omega_b)} \right]$$

and the conductivity in the direction of the field is given by

$$\sigma_H = \frac{1}{2}(\sigma_c + \sigma_0).$$

and $$\sigma_H = \frac{e^2 n}{m} \left[\left\{ \frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2} \right\} \right.$$

$$\left. - j \left\{ \frac{(\omega - \omega_b)}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{(\omega + \omega_b)}{\nu_c^2 + (\omega + \omega_b)^2} \right\} \right]$$

so that real part of the conductivity is given by

$$\sigma_{rH} = \frac{e^2 n}{m} \left[\frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_e^2 + (\omega + \omega_b)^2} \right]$$

and after simplification it reduces to the result obtained earlier by Appleton and Boohariwalla (1935)

$$\sigma_{rH} = \frac{e^2n}{m} \frac{\nu_c[\nu_c^2+\omega_b^2+\omega^2]}{(\nu_c^2+\omega^2+\omega_b^2)^2-4\omega^2\omega_b^2}$$

Though some measurements of radio-frequency conductivity have been carried our earlier it is felt necessary that a thorough and systematic experimental measurement of radio frequency conductivity of ionized gases in a magnetic field will yield some data which can be utilized for the verification of the theory advanced by Gilardini (1959) or by Appleton and Boohariwall (1935). Also it will be of interest to study the variation of radio-frequency conductivity in a magnetic field and to see how the pressure at which the conductivity becomes a maximum varies with the application of the magnetic field. An idea regarding the interaction of the magnetic field with the ionized gases can thus be obtained. With this object in view the present work has been undertaken and the paper reports the results obtained experimentally in case of air and carbondioxide in presence of magnetic field varying from 0 to 700 gauss and the pressure varying from a few microns to 300 microns.

EXPERIMENTAL PROCEDURE

The radio-frequency conductivity of ionized gases such as air and carbondioxide has been determined in the same way as has been done by (Sen and Ghosh, *1966). Pure and dry air has been used and carbondioxide has* been prepared by letting a saturated solution of oxalic acid (analytical grade) in water fall drop by drop in to a saturated solution of sodiumbicarbonate (analytical grade). The evolved carbondioxide was passed through phosphorus pentoxide to remove water vapour. The magnetic field has been supplied by an electromagnet and the lines of force are perpendicular both to the direction of the field and to the length of the discharge tube. Keeping the magnetic field constant at a particular value, the pressure of the gas has been varied and the conductivity of the gas determined for various values of the pressure, and the same procedure has been repeated for various values of the magnetic field. The experiment has been repeated a large number of times and the results have been found to be consistent. The pressure of the gas has been measured as was done in the previous papers, (Sen *et. al.*, 1962, a, b). The frequency of the applied field as measured by a wide band communication receiver was 10.6 Mc/sec and measurements were taken for the value of the discharge current of 20mA. The values of the magnetic field have been measured accurately by a calibrated Fluxmeter.

RESULTS AND DISCUSSION

The variation of radio-frequency conductivity against pressure has been plotted in case of air and carbondioxide for different values of the magnetic field in Fig. 1 and Fig. 2; also the conductivity pressure curve without magnetic field

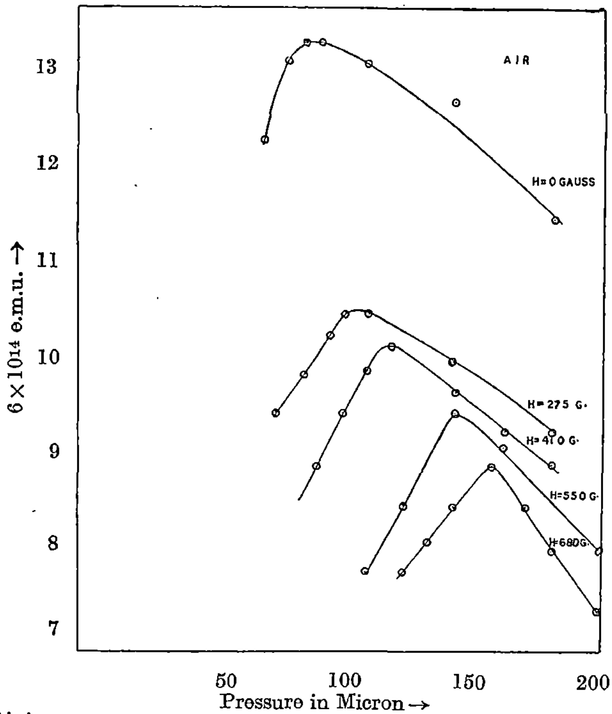

Fig. 1. Conductivity of ionised air against pressure for different values of the magnetic field.

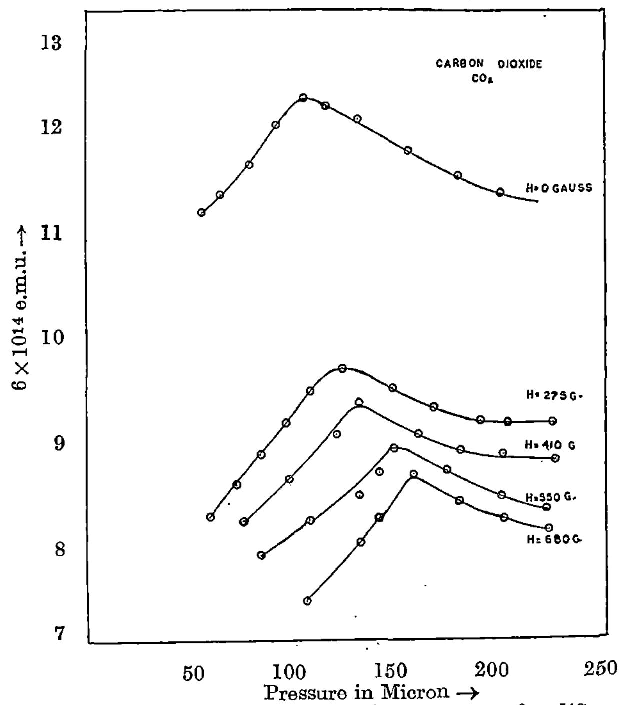

Fig. 2. Conductivity of ionised carbondioxide against pressure for different values of the magnetic deld.

has been given for comparison. It is observed that the value of σ_r is smaller when magnetic field is present than that without field for all values of pressure and the pressure at which the conductivity becomes a maximum always shifts to higher pressure when the magnetic field is increased. That the real part of r.f. conductivity will be smaller in presence of magnetic field than when the field is absent is evident from the following considerations; we have

$$\sigma_r = \frac{ne^2}{m} \cdot \frac{\nu_c}{\nu_c^2+\omega^2}$$

and

$$\sigma_{rH} = \frac{ne^2}{m} \cdot \frac{\nu_c(\nu_c^2+\omega^2+\omega_b^2)}{(\nu_c^2+\omega^2+\omega_b^2)^2-\omega^2\omega_b^2}\,.$$

so that when the magnetic field employed is of the order of 200 gauss, we get

$$\omega = 3.52\times 10^9 \text{ radians}$$

and for $H = 300$ Gauss, $\omega = 5.28\times 10^9$ radians

whereas the frequency of the applied field is of the order of 2.95×10^6 cycles/sec or 1.852×10^7 radians; we can therefore neglect ω in comparison to ω_b and hence obtain

$$\sigma_{rH} = \frac{ne^2}{m} \cdot \frac{\nu_c(\nu_c^2+\omega_b^2)}{(\nu_c^2+\omega_b^2)^2-4\omega^2\omega_b^2}\,.$$

then

$$\frac{\sigma}{\sigma_{rH}} = \frac{(\nu_c^2+\omega_b^2)^2-4\omega^2\omega_b^2}{(\nu_c^2+\omega_b^2)(\nu_c^2+\omega^2)}\,.$$

and neglecting $4\omega^2\omega_b^2$ in comparison to $(\omega_b^2+\nu_e^2)^2$ we get

$$\frac{\sigma}{\sigma\pi_H} = \left(\frac{1+\omega_b^2/\nu_c^2}{1+\omega^2/\nu_c^2}\right)$$

and since $\omega_b >> \omega$, $\sigma/\sigma_{\gamma H}$ will be greater than unity as is actually found to be the case in the range of pressure investigated. Considering from the physical point of view it is seen that due to the presence of magnetic field the effective mean free path is shortened and now there is a greater number of collisions which results in a net reduction of the number of drifting electrons contributing to the conductivity current and hence the conductivity decreases. However, in the discussion which follows it will be assumed that the number of electrons per unit volume is the same in the presence of magnetic field as in its absence, because it is clearly observed in the course of experiment as well as from theoretical considerations that there is a gradation of concentrations of electrons in the path of the radio-frequency field but the average number approximately remains the same.

The values of pressure at which the conductivity becomes maximum in case of air and carbondioxide have been obtained from the curves of Fig. 1 and 2 and entered in Table I.

TABLE I

Gas	Magnetic field in gauss	Value of maximum conductivity $\times 10^{14}$ e.m.u.	Corresponding pressure as from experiment in micron.	(P_H) min from equ. (2) (microns) (4)	(P_H) min from equn (4) in micron
Air	0	13.175	92		
	275	10.475	112	115.7	92.56
	410	10.125	123	118.8	95.04
	550	9.175	150	130.02	104.016
	680	8.923	170	136.66	109.33
Carbondioxide	0	12.6	108		
	275	9.85	125	140.7	112.56
	410	9.45	140	146.7	117.36
	550	9.00	155	154.0	123.2
	680	8.725	162	157.9	127.12

It is evident that the maximum value of conductivity diminishes and the pressure at which the conductivity becomes a maximum shifts to higher values whth the application of the magnetic field. To explain this it is observed that since $\omega_b >> \omega$ for the values of magnetic field employed,

$$\sigma_{rH} = \frac{ne^2}{m} \cdot \frac{\nu_c}{\nu_c^2 + \omega_b^2}$$

and putting
$$\nu_c = \frac{v_r}{\lambda} = \frac{v_r P}{L}$$

where L is the mean of free path of the electron in the gas at a pressure of $1mm$ v_γ the velocity of the electrons we get,

$$\sigma_{rH} = \frac{ne^2}{m} \cdot \frac{L}{v_r} \cdot \frac{P}{P^2 + C_1 H^2}$$

where
$$C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r}\right)^2.$$

and σ_{rH} will be a maximum with respect to P

when $$(P_H)_{max}^2 = C_1 H^2.$$

where $(P_H)_{max}$ is the pressure at which the conductivity becomes a maximum in presence of magnetic field.

then $$(\sigma_{rH})_{max} = \frac{1}{2} \cdot \frac{ne^2}{m} \cdot \frac{L}{v_r} \cdot \frac{1}{(P_H)_{max}} \cdot$$

and $$(\sigma_r)_{max} = \frac{1}{2} \cdot \frac{ne^2}{m} \cdot \frac{L}{v_r} \cdot \frac{1}{P_{max}} \cdot$$

so that $$(P_H)_{max} = \frac{(\sigma_r)_{max}}{(\sigma_{rH})_{max}} \cdot P_{max} \cdot \tag{2}$$

The values of $(\sigma_r)_{max}$ and $(\sigma_{rH})_{max}$ as well as P_{max} can be obtained from experimental data and hence $(P_H)_{max}$ can be calculated. The results calculated from equation (2) have been entered into the fifth column of the Table I; the agreement is quite satisfactory considering the simplifications involved in the deduction of the equation. The result also shows that the pressure at which the radio-frequency conductivity becomes maximum always shifts to higher values as the magnetic field is increased. The above deduction cannot be taken as rigorous because in presence of a magnetic field the actual pressure is changed to an effective pressure as has been shown by Blevin and Haydon, (1958)

$$P_H = P\sqrt{1+C_1H^2/P^2}.$$

where $$C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r}\right)^2.$$

Due to this change of pressure the collision frequency also changes. Gilardini (1959) in developing his theory has not taken this change into consideration and assumed that the collision frequency is same both with the without magnetic field. Hence

$$\sigma_{rH} = \frac{ne^2}{m} \cdot \frac{L}{v_r} \cdot \frac{[P^2+C_1H^2]^{\frac{1}{2}}}{P^2+2C_1H^2} \quad \dots \quad (3).$$

he condition for obtaining the maximum value of σ_{rH} when its variation with pressure is taken into consideration is obtained from equation (3). This occurs when $P = 0$ which is anomalous. It may be recalled that Appleton and Booharie-walla (1935), without taking into consideration the concept of equivalent pressure also came to the same conclusion from graphical analysis. Consequently if we adopt the Blevin and Haydon expression in this case, it leads to result which is anomalous. Of course the validity of Belvin and Haydon's expression has previously been tested in case of air by Sen and Ghosh (1961) where it was shown that for values of pressure less than 150μ and magnetic field of the order of 100 gauss the expression gives values of equivalent pressure different from the actual pressure. Since the pressure at which maxima are occuring is in a region greater than 100μ, and the magnetic field employed is also large it can be conjectured that Blevin and Haydon's expression does not hold in the region of pressure where maxima are occuring.

Townsend and Gill (1937) on the otherhand deduced that

$$\mu_H = \frac{\mu}{1+\omega_b{}^2\tau^2}.$$

where μ_H is the mobility of electrons in the magnetic field H; τ is the time between successive collisions and $\omega_b = eH/m$. It can be deduced from the above relation that

$$P_H = P\left[1+C_1\frac{H^2}{P^2}\right]$$

and hence
$$\sigma_{rH} = \frac{ne^2}{m}\cdot\frac{L}{v_r}\cdot\frac{P[P^2+C_1H^2]}{[(P^2+C_1H^2)^2+C_1H^2P^2]}.$$

and σ_{rH} is maximum when $(P_H)_{max} = C_1H^2$.

then
$$(\sigma_{rH})_{max} = \frac{ne^2}{m}\cdot\frac{L}{v_r}\frac{1}{(P_H)_{max}}\cdot\frac{2}{5}.$$

and as
$$(\sigma_r)_{max} = \frac{ne^2}{m}\cdot\frac{L}{v_r}\cdot\frac{1}{P_{max}}\cdot\frac{1}{2}.$$

we get
$$(P_H)_{max} = \frac{(\sigma_r)_{max}}{(\sigma_{rH})_{max}}\cdot\frac{4}{5}\cdot(P_H)_{max}. \qquad \dots (4)$$

The results calculated from equation (4) are entered into the last column of Table I. It is observed that results obtained with equation (4) are in wide disagreement with the experimental results both in the case of air and carbondioxide. It is thus evident that the concept of equivalent pressure whether from Blevin and Haydon expression or from Townsend expression can not lead to any imporvement in the theoretical deduction.

It can thus be conluded that in case of air and carbondioxide the simple theory put forward by Gilardini can explain the results quite well specially when the gyro-frequency is far removed from the frequency of the measuring field but this treatment is over simplified. Further it has been shown that the inclusion of the concept of equivalent pressure does not lead to any better results. In fact Haydon (1961) has discussed the limitation of the equivalent pressure concept in which he found different values of C_1 for Hydrogen by plotting (α_H/α_0) where α is the first Townsend coefficient against values of (H/E) varying from 0 to 2.5 where E is the breakdown voltage. From this he has concluded that perhaps drift velocity is a linear function of (E/P) for small (E/P) values but varies as $(E/P)^n$ where $n > 1$ for large (E/P) values. The value of E/P in these experiments is of the order of 150 volts/cm mm of Hg and hence the linearity relation between the drift velocity and (E/P) on which the Blevin Haydon expression is based, may not hold good for the values of (E/P) used here. This may partly account for the failure of the conception of equivalent pressure in explaining the observed results. The limitations of equivalent pressure concept have also been discussed previously by Sen and Ghosh (1961) where it was shown that the expression is valid upto a pressure of 150μ when the magnetic field is of the order of 100 gauss. Since the magnetic field used here is much greater than 100 gauss, and the maxima are also occuring at pressures greater than 150μ, the Blevin Haydon expression cannot be expected to hold here. Experiments are in progress in this laboratory to measure the radio-frequency conductivity in other gases specially in inert gases and the results will be reported in future.

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Plasma Parameters from rf Conductivity Measurements

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Radio frequency conductivity measurements have been made in the case of 3 ionized gases, viz. helium, neon and argon, over the pressure range of a few microns to 700 μ and under an external magnetic field varying from 0 to 550 gauss. From the experimentally determined values of σ_r, the real part of rf conductivity, it has been possible to calculate the electron density, the collision frequency and electron temperature and study their variation with pressure, the discharge current and magnetic field. A quantitative theory has been proposed to explain the variation of electron temperature with magnetic field and the experimental data compare well with the theoretical variation, specially at low values of pressure and magnetic field. The pressure $(P_H)_{max}$ at which the rf conductivity becomes maximum shifts to higher values with the increase in the magnetic field for all the gases studied. Good quantitative agreement between the values of $(P_H)_{max}$, derived on the basis of the concept of equivalent pressure and variation of random velocity with magnetic field, and the experimental values is observed. The dielectric constant and the Debye shielding distance have been obtained from values of σ_r and their variation with magnetic field and pressure has been studied. A qualitative explanation of the variation of these two parameters has been suggested.

IN continuation of the work done previously by Sen and Ghosh[1] and Gupta and Mandal[2], the rf conductivity of ionized gases such as helium, neon and argon has been determined by the present authors, the pressure varying from a few microns to 700 μ. In the previous paper by Sen and Ghosh[1], a new method for measuring the rf conductivity of ionized gases has been reported and it has been shown that from these measurements it is possible to calculate parameters, such as collision frequency, electron density and electron temperature of the discharge. A precise knowledge of these parameters, their variation with the pressure and the externally applied magnetic field is essential for a proper understanding of the mechanism operating in the discharge. As pointed out earlier, some measurements of this nature have been carried out in the microwave region, but data in the rf region are very rare. Further, this method supplements the standard methods in plasma diagnostics and gives accurate values and also helps in the elucidation of the nature of variation of these parameters in an externally applied field. In an earlier paper by Gupta and Mandal[2] it has been shown that the rf conductivity is strongly dependent upon the magnetic field applied and a theory has been developed to explain the observed results in case of air and carbon dioxide. In order to verify the theory further, and to study the variation of plasma parameters in externally applied magnetic field, it has been decided to examine the results in other gases also and the present paper reports the results in case of helium, argon and neon in a magnetic field which has been varied from 0 to 550 gauss.

Experimental Arrangement

The method of measuring the rf conductivity of ionized gases has been described in the previous paper[1]. Spectroscopically pure samples of gases employed have been supplied by Messrs British Oxygen Gases Ltd, Wembley. The whole system was continuously evacuated for a number of days and then flushed with the gas under examination several times before measurements were undertaken. The pressure was very carefully measured by an Edward Penning Pirani vacuum gauge. The measurements were repeated a large number of times and the data have been found to be consistent. The magnetic field supplied by an electromagnet has been measured by a calibrated fluxmeter. The frequency of the rf voltage supplied by a tuned-plate tuned-grid oscillator is 10·2 Mc/s, as measured by a standard communication receiver. The discharge was excited by a transformer.

Results and Discussion

The variation of σ_r, the real part of the rf conductivity, with pressure has been plotted in Fig. 1 for helium, argon and neon for a representative value of the discharge current, viz. 15 mA. In all the gases studied, the rf conductivity gradually increases with pressure, attains a maximum value at a certain pressure which is different for different gases and then gradually falls in accordance with the formula of Sen and Ghosh[1]:

$$\sigma_r = \frac{ne^2}{m} \cdot \frac{\nu_c}{\nu_c^2+\omega^2}$$

It is observed that the maximum value of conductivity occurs at the same pressure for different values of the discharge currents for the same gas and the maximum value itself increases with the increase of discharge current. The condition for σ_r to be maximum is obtained when $\nu_c = \omega$, which is valid only when the electron density does not change with pressure. Appleton and Chapman[3] using a Langmuir probe showed that n does not change with pressure. Since n can be taken as a measure of the degree of ionization, change of pressure alone will not materially effect the value of n

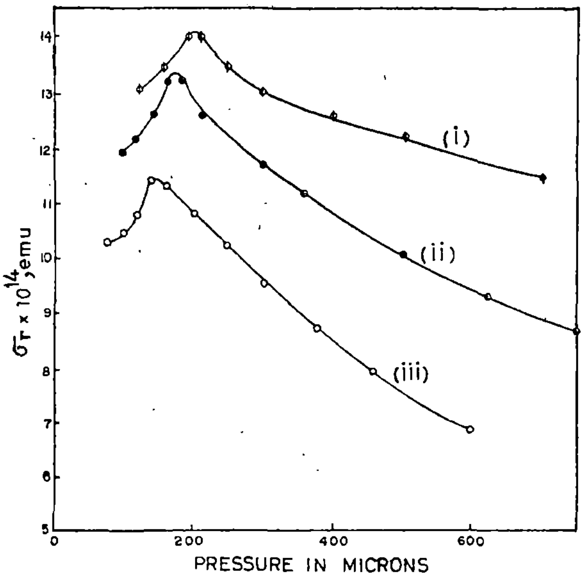

Fig. 1 — Variation of σ_r with pressure for a discharge; current of 15 mA for different gases [(i) helium; (ii) neon and (iii) argon]

and it can be regarded as a constant to a first approximation when the pressure is gradually changing. Since the applied frequency does not change, the maxima should occur at the same value of pressure irrespective of discharge current. The value of n can then be calculated from the relation

$$(\sigma_r)_{\max} = \frac{ne^2}{2m\omega} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots (1)$$

The values of n corresponding to the pressure at which $\nu_c = \omega$ have been computed and are given in Table 1 for all the three gases and for different discharge currents. From Table 1 it is evident that n is not proportional to discharge current but has a tendency to assume a saturation value as the current increases, in case of all the three gases, which fact is also evident from the ratio (n/i) entered into the last column of Table 1. Since the current $i = nev$, it follows that the velocity (v) of the electron should increase due to increased voltage applied to get higher discharge currents.

As

$$\sigma_r = \frac{ne^2}{m} \cdot \frac{\nu_c}{\nu_c^2+\omega^2} \quad \text{and} \quad (\sigma_r)_{\max} = \frac{ne^2}{2m\omega}$$

it can be deduced that

$$\nu_c = \omega\left[\frac{(\sigma_r)_{\max}}{\sigma_r} \pm \sqrt{\frac{(\sigma_r)^2_{\max}}{(\sigma_r)^2} - 1}\right] \quad \ldots \quad \ldots \quad \ldots (2)$$

Hence, it is possible to calculate the collision frequency of the electron at different pressures for different gases and from the relation $\nu_c = v_r/\lambda_e$ where λ_e is the mean free-path of the electron in the gas, v_r can be calculated. Value of λ_e has been calculated from the relation $\lambda_e = L/P$, where L is the mean free-path of the electron at a pressure of 1 mm and $L = 1/A_0$ where A_0 is the coefficient introduced by Townsend in his theory of electrical breakdown of gases; the values of A_0 for different

TABLE 1 — CALCULATED VALUES OF ELECTRON DENSITY n AT DIFFERENT VALUES OF DISCHARGE CURRENT

Gas	Discharge current mA	Pressure for $(\sigma_r)_{\max}$ μ	$(\sigma_r)_{\max}$ $\times 10^{14}$ emu	$n \times 10^{-8}$ as calculated from Eq. (1)	$(n/i) \times 10^{-10}$
Argon	10		10·5	0·468	0·468
	15	145	11·42	0·5105	0·3403
	20		12·45	0·5433	0·2717
Neon	10		11·25	0·5023	0·5023
	15	170	13·3	0·594	0·396
	20		14·95	0·6674	0·3337
Helium	10		12·28	0·5483	0·5483
	15	200	14·02	0·626	0·417
	20		15·5	0·692	0·346

gases have been obtained from Von Engel[4]. Further, since $v_r = \sqrt{8KT_e/m\pi}$, the values of electron temperature (T_e) can be calculated and the values thus obtained have been plotted in Fig. 2 against the corresponding pressure for helium as a representative case. The variation of electron temperature with pressure indicates that the fall is rather rapid with pressure at low pressures but at higher pressures it practically remains unchanged. The nature of variation is the same in case of all the gases studied here as was found previously by Sen and Ghosh[1] in case of air and nitrogen. The results are also quite similar to those obtained in case of arc plasma by Bohm *et al.*[5] and further it is noted that there is little variation of electron temperature with the change of discharge current. The change with pressure has been ascribed by Bohm *et al.* to the greater number of inelastic collisions which the electron suffers with the gas molecules and as an appreciable fraction of electrons will possess energy sufficient to excite and even to ionize the gas molecules, it is expected that the electron temperature which is a measure of the remaining energy of the electrons will decrease with the increase of pressure; because due to increasing number of inelastic collisions, the energy transferred by the electrons to the atoms will increase.

It has been found that the Maxwellian distribution is a good approximation for molecular gases where

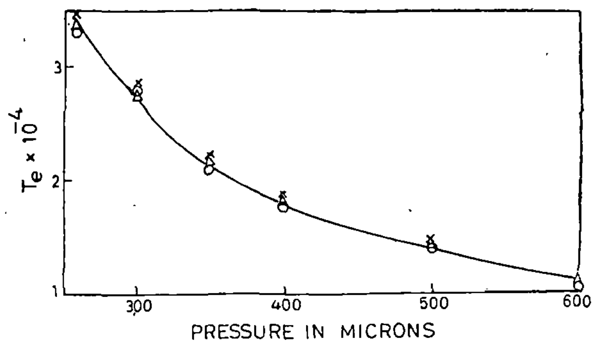

Fig. 2 — Variation of T_e with pressure for different discharge currents through helium [o, 10 mA; △, 15 mA; and ×, 20 mA]

the excitation levels including the vibrational ones are widely spread out up to ionization level. Hence, inelastic losses set up at relatively low energies and though the average electron energy is low, the losses are so distributed as to produce an approximately Maxwellian distribution. In rare gases, however, the excitation levels are much closer to ionization level, hence for low values of (E/P), only elastic losses are important. The average energy is much higher than in molecular gases at the same value of (E/P) and Druyvesteyn distribution holds. The fact that the electron temperature becomes constant for large values of pressure can be explained by the fact that elastic losses predominate and there is no change of electron energy. Further, as $\nu_c = v_r/\lambda_e$, and due to Townsend-Ramsauer effect λ_e is not a constant but varies with the electron energy, the random velocity and hence the electron temperature becomes a function of pressure.

From the theory of the positive column and assuming Maxwell-Boltzmann distribution law, Von Engel[4] deduced that

$$\frac{e^x}{x^{\frac{1}{2}}}=1\cdot2\times10^7(CPR)^2 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots(3)$$

where $x=eV_i/KT_e$ and C is a constant $=(aV_i^{\frac{1}{2}}/K^+P)^{\frac{1}{2}}$; R, the radius of the tube; P, the pressure; V_i, the ionization potential of the gas; and K^+, the mobility of the positive ions and a is the efficiency of ionization, the values of a for different gases have been given by Von Engel[4].

From Eq. (3) it can be deduced that

$$\frac{dT_e}{dP}=\frac{KT_e^2/eV_i}{P\left[\frac{KT_e}{2eV_i}-1\right]} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots(4)$$

In general, the values of electron temperature in rare gases is of the order of 10^4 and $KT_e/2eV_i$ becomes smaller than 1; hence dT_e/dP is negative; that is, the values of electron temperature diminish with the increase of pressure. The nature of variation is shown in different curves obtained for the rare gases. The general variation of T_e with pressure can thus be explained at least qualitatively by assuming that the electrons follow a Maxwellian distribution law though the electrons in rare gases do not actually follow this distribution.

Variation of electron temperature in magnetic field — The rf conductivity of ionized gases has been measured in magnetic field as in the previous paper by Gupta and Mandal[2]; the electron temperature has been calculated as before at a particular pressure for different values of the magnetic field and the variation of T_e with magnetic field has been plotted for different gases in Fig. 3. The values of electron temperature have been plotted for magnetic fields varying from 0 to 550 gauss and in case of all the three gases, the electron temperature decreases in the presence of the field, rapidly at first and then slowly. Bickerton and Von Engel[6] studied the variation of electron temperature in the positive column in helium in the presence of a longitudinal magnetic field, making measurements with Langmuir probe. The nature of variation of electron temperature is the same as has been obtained in the present investigation. Bickerton

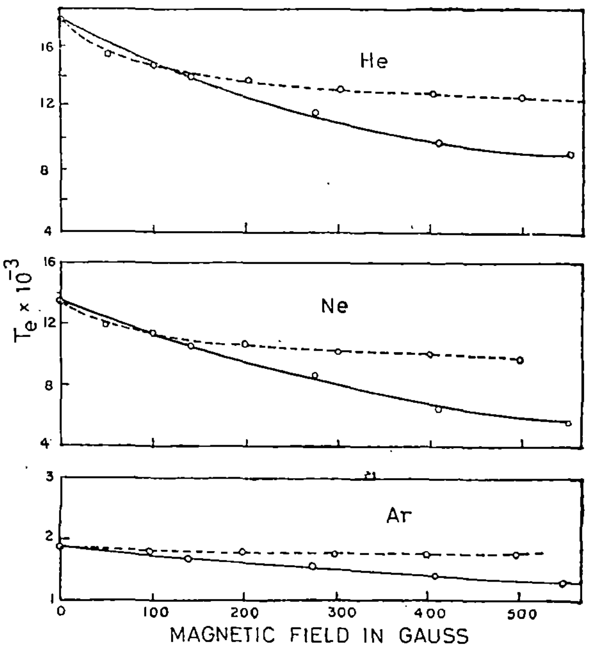

Fig. 3 — Variation of T_e with magnetic field for different gases [——, exp.; and - - -, theo.]

and Von Engel[6] attributed the decrease in electron temperature to the influence of magnetic field on the ambipolar diffusion coefficient. This is equivalent to saying that the pressure in the presence of magnetic field becomes the equivalent pressure as has been shown by Blevin and Haydon[7] so that

$$P_H = P[1+C_1 H^2/P^2]^{\frac{1}{2}}$$

where

$$C_1 = \left(\frac{e}{m}\cdot\frac{L}{v_r}\right)^2$$

where L is the mean free-path of the electrons at a pressure of 1 mm of Hg and v_r the random velocity. Hence starting from expression (3) and remembering that the mobility coefficient K^+ of the positive ions is practically unaffected by a magnetic field H due to their larger mass, we get when the magnetic field is present the following expression:

$$\frac{eV_i/KT_{eH}}{\left(\frac{eV_i}{KT_{eH}}\right)^{\frac{1}{2}}}=\frac{1\cdot2\times10^7aV_i^{\frac{1}{2}}}{K^+}R^2P_H \quad \ldots \quad \ldots \quad \ldots(5)$$

where T_{eH} is the electron temperature in the presence of magnetic field. We get from Eqs. (3) and (5)

$$\sqrt{\frac{T_{eH}}{T_e}}\cdot e^{\frac{eV_i}{K}\cdot\frac{T_{eH}-T_e}{T_{eH}.T_e}}=\frac{P}{P_H}=\frac{1}{\sqrt{1+C_1 H^2/P^2}}$$

The quantity

$$\frac{eV_i}{K}=\Upsilon \text{ (say) and let } \beta=\frac{1}{\sqrt{1+C_1 H^2/P^2}}$$

and hence

$$\log\frac{T_{eH}}{T_e}+\frac{2\Upsilon(T_{eH}-T_e)}{T_e.T_{eH}}=2\log\beta$$

since from experimental results, $T_{eH}/T_e<1$ and for values of T_{eH} not much different from T_e

$$T_{eH}=T_e+\frac{2T_e^2\log\left[\frac{1}{\sqrt{1+C_1 H^2/P^2}}\right]}{T_e+2eV_i/K} \quad \dots \quad \dots(6)$$

The values of the terms appearing in Eq. (6) have been calculated as follows. In calculating the values of $C_1=(e/m.L/v_r)^2$ the random velocity has been obtained from the relation $v_r=\nu_c\lambda_e$ for maximum value of conductivity and L is the mean free-path of the electrons at a pressure of 1 mm of Hg, which has been obtained from the relation $L=1/A_0$ where A_0 is the constant appearing in Townsend's equation and whose values are given by Von Engel[4] for different gases. Value of eV_i/K has been calculated from the known values of the ionization potential and the values have been entered in Table 2.

The theoretical values of electron temperature calculated from the above equation and for different values of the magnetic field have been plotted in Fig. 3 side by side with the experimental curves. The general nature of the curve is almost of the same form as the experimental curve and the quantitative disagreement may be ascribed to the uncertainty in the values of C_1, and the random velocity which has been assumed in the calculation is actually found to change with magnetic field. The quantitative agreement is satisfactory specially for low values of magnetic field below 100 gauss in the case of all the three gases and this is due to the fact that the equivalent pressure expression from which this formula has been deduced is valid for low magnetic fields only as has also been observed in the previous paper.

TABLE 2 — VALUES OF C_1 AND $2eV_i/K$ FOR HELIUM, NEON AND ARGON

Gas	C_1	$2eV_i/K$
He	$5{\cdot}035\times10^{-3}$	$5{\cdot}74\times10^{5}$
Ne	$3{\cdot}765\times10^{-3}$	$5{\cdot}035\times10^{5}$
Ar	$2{\cdot}16\times10^{-3}$	$3{\cdot}713\times10^{5}$

Variation of rf conductivity with pressure and magnetic field — As in the previous paper[2], the rf conductivity of the ionized gases has been measured in the presence of magnetic field varying from zero to 550 gauss. It is observed that the value of rf conductivity decreases for all values of magnetic field and the pressure at which the conductivity becomes a maximum shifts to higher values with the increase of the magnetic field; that the value of rf conductivity will decrease can be explained as in the previous paper where it was shown that

$$\frac{\sigma_r}{\sigma_{rH}}=\frac{1+\omega_b^2/\nu_c^2}{1+\omega^2/\nu_c^2}$$

where $\omega=eH/mc$ and as $\omega_b\gg\omega$, σ_r will be greater than σ_{rH} for all values of the magnetic field. The shift in the value of pressure for maximum conductivity has been calculated from the derived equation in the previous paper where it was shown that

$$(P_H)_{\max}=\frac{(\sigma_r)_{\max}}{(\sigma_{rH})_{\max}}\cdot P_{\max} \quad \dots \quad \dots \quad \dots(7)$$

The values of $(P_H)_{\max}$ calculated from the above expression have been entered in the sixth column of Table 3 where $(P_H)_{\max}$ is the pressure at which the conductivity becomes a maximum in the presence of magnetic field and $P_{\max}$ the pressure at which the conductivity becomes maximum in the absence of magnetic field.

It is thus seen that there is some agreement between the values of $(P_H)_{\max}$ calculated and these observed experimentally specially for low values of magnetic field in the case of all the three gases studied and the disagreement is more pronounced

TABLE 3 — EXPERIMENTAL AND THEORETICAL VALUES OF $(P_H)_{\max}$ FOR DIFFERENT VALUES OF MAGNETIC FIELD

Gas	Magnetic field gauss	$(\sigma_r)_{\max}\times10^{14}$ emu	Random velocity as calculated from $\nu_c=v_r/\lambda_e$ $v_r\times10^{-8}$ cm/sec	$(P_H)_{\max}$ in micron from experiment	$(P_H)_{\max}$ in micron from Eq. (5)	$(P_H)_{\max}$ in micron from Eq. (6)
He	0	12·275	8·28	200		
	140	10·675	7·34	242	230·0	259
	275	10·100	6·803	282	243·1	295
	410	9·725	6·166	320	252·4	338·4
	550	9·500	5·82	352	258·4	343·2
Ar	0	10·56	2·704	148		
	140	9·13	2·56	168	171·2	174·5
	275	8·8	2·43	184	177·6	197·6
	410	8·53	2·33	202	183·2	212·3
	550	8·2	2·18	222	190·6	243·1
Ne	0	11·3	7·17	172·5		
	140	10·1	6·36	210	193·1	217·3
	275	9·55	5·77	250	204·1	254·1
	410	8·9	4·95	300	219·1	317·4
	550	8·5	4·59	350	229·4	358·1

for high values of magnetic field. But this formula has to be modified because it has been observed that the electron temperature and hence random velocity becomes a function of the magnetic field. In deducing Eq. (5) it was assumed that $v_r = v_{rH}$ but as v_r varies with magnetic field

$$(\sigma_r)_{\max} = \frac{ne^2}{2m} \cdot \frac{L}{v_r} \cdot \frac{1}{P_{\max}}$$

and

$$(\sigma_{rH})_{\max} = \frac{ne^2}{2m} \cdot \frac{L}{v_{rH}} \cdot \frac{1}{(P_H)_{\max}}$$

Hence

$$(P_H)_{\max} = \frac{v_r}{v_{rH}} \cdot \frac{(\sigma_r)_{\max}}{(\sigma_{rH})_{\max}} \cdot P_{\max} \quad \ldots \quad \ldots(8)$$

The values of v_r and v_{rH} as calculated from the maximum values of conductivity have been entered in column 4 of Table 3 for the three gases and the values of $(P_{\bar{H}})_{\max}$ as calculated from Eq. (6) have been entered in the last column of Table 3. It is clear that when the formula is thus modified it gives very good agreement with the observed experimental results. As has been noted in the previous paper, the range of validity of equivalent pressure is very limited and specially it fails for high values of magnetic field. Further, the expression for equivalent pressure was deduced on the assumption that electron distribution is mainly governed by Maxwell-Boltzmann distribution which holds specially for molecular gases and it is known that electron distribution in rare gases is not governed by Maxwell-Boltzmann law which may account to a certain extent the observed discrepancy.

Dielectric constant of plasma — It is further observed that besides the above parameters, the dielectric constant of the plasma can also be determined from the measured rf conductivity of the ionized gas. It is well known that the dielectric constant of a plasma is given by

$$\epsilon = 1 - \frac{4\pi ne^2}{m\omega^2}$$

and this treatment neglects the collisions between electrons and ions and neutral molecules. However, when this is taken into consideration ϵ^* the complex dielectric constant is given by

$$\epsilon^* = \epsilon' - J\epsilon''$$

where

$$\left.\begin{aligned} \epsilon' &= 1 - \frac{4\pi ne^2\omega}{m(\nu_c^2+\omega^2)\omega} = \left[1 - \frac{4\pi\sigma_i}{\omega}\right] \\ &\text{and} \\ \epsilon'' &= \frac{4\pi}{\omega} \cdot \frac{ne^2}{m} \cdot \frac{\nu_c}{\nu_c^2+\omega^2} = \frac{4\pi\sigma_r}{\omega} \end{aligned}\right\} \quad \ldots \quad \ldots(9)$$

where σ_r and σ_i are the real and imaginary parts of rf conductivity. The dielectric properties of ionized gases were measured by Gutton and Clement[8] and Gutton[9] who used the energized plasma to terminate a lecher line. Adler[10] measured the conductivity of ionized gases in the microwave region and Dutt[11] has also measured the dielectric properties of the rare gases in the afterglow plasma.

The values of σ_r have been experimentally determined for helium, argon and neon over a pressure range of a few microns to 700 μ and in the presence of a magnetic field, varying from 0 to 550 gauss and hence the value of ϵ'' can be calculated from Eq. (7) and its variation with pressure can be studied. Such calculations have been made in the case of helium, argon and neon for a range of pressures of a few microns to 600 μ from the measured values of σ_r and the variation plotted in Fig. 4. It is seen that ϵ'' becomes a maximum when σ_r becomes a maximum and this takes place when the collision frequency becomes equal to the applied frequency. Since ϵ'' is the loss factor of the dielectric constant and the loss will evidently become a maximum when σ_r is a maximum; ϵ' can also be calculated if σ_i is measured.

When the plasma is placed in the magnetic field which is at right angles both to the direction of discharge current and the rf field it has been noted that σ_r diminishes and the pressure at which it becomes a maximum is shifted to higher values of pressure. Similar behaviour is also observed in the case of ϵ'' in the magnetic field. The variation of ϵ'' in the magnetic field for different values of pressure is plotted side by side in Fig. 4.

The Debye shielding distance λ_D is given by

$$\lambda_D^2 = \frac{KT_e}{4\pi ne^2}$$

and n can be obtained from the relation

$$(\sigma_r)_{\max} = \frac{ne^2}{2m\omega}$$

The evaluation of T_e the electron temperature and its variation in the magnetic field has been studied in case of rare gases here. From the above available data the variation of Debye shielding distance for a fixed pressure and variable magnetic field has been plotted in Fig. 5 for the three gases. The order of magnitude of λ_D is found to be of the same order as has been calculated by Glasstone and Lovberg[12] for large electron densities and high electron temperature as are obtained in the case of thermonuclear plasma. Thus, from the variation of λ_D with pressure as well as with magnetic field it

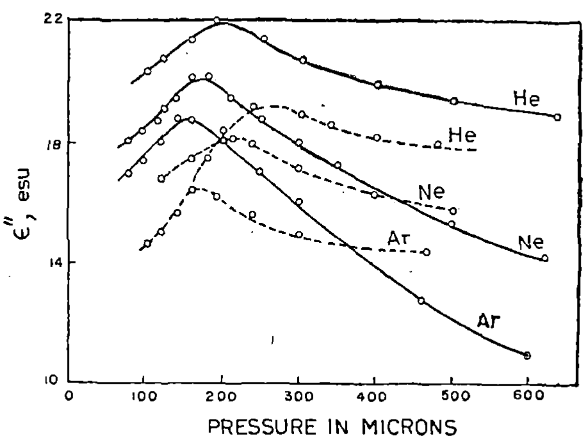

Fig. 4 — Variation of ϵ'' with pressure for helium, argon and neon [——, without field; and - - -, with field]

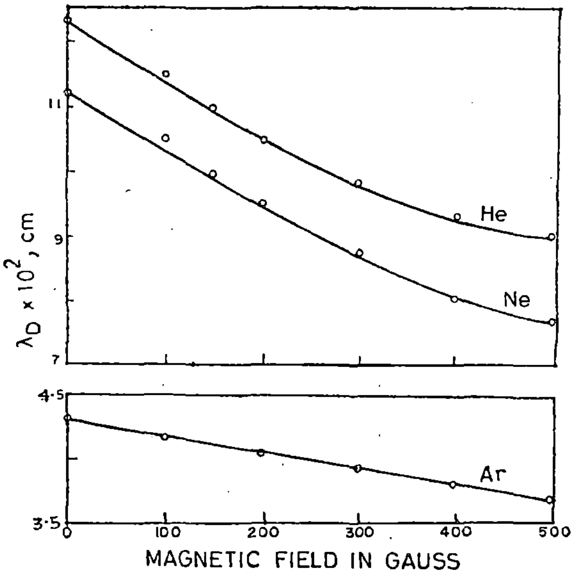

Fig. 5 — Variation of λ_D with magnetic field for helium, neon and argon

is observed that the decrease is linear up to 200 gauss in case of helium and up to approximately 300 gauss in case of neon. In case of argon the linearity is maintained almost up to 500 gauss; above these respective magnetic fields or pressures there is practically little change of λ_D. Arqualitative correlation can be established between the change of Debye length and the mean free-path of electrons in these gases. It is noted that the mean free-path of electrons in case of He, Ne and Ar can be calculated from Townsend coefficient A_0 where $A_0 = 1/L$, L being the mean free-path of electron at a pressure of 1 mm. Value of A_0 in case of helium, neon and argon being 3, 4 and 14 respectively (Von Engel[4]) and hence the mean free-path at a pressure of say 300 μ is 1·2, 1·0 and 0·288 cm respectively for the three gases. The Debye shielding distance is much smaller than the mean free-path at this pressure and shows a decrease with increase of pressure, but at higher pressure when the mean free-path becomes comparable to λ_D the change becomes very small. The concept of equivalent pressure (Blevin and Haydon[7]) shows that the equivalent pressure increases with the magnetic field and hence the change of λ_D with magnetic field can be explained on the same basis as that due to change of pressure.

It can thus be concluded from the above discussion that it is possible from the measurements of rf conductivity to evaluate the various parameters of a plasma and also to study the variation of these parameters with pressure and externally applied magnetic field. These studies further throw considerable light into the processes operating in the discharge.

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ELECTRON TEMPRATURE AND DEBYE SHIELDIGN DISTANC IN HYDROGEN PLASMA IN A TRANSVERSE MAGNETIC FIELD

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ABSTRACT.

A method has been developed for the measurement of electron temperature and Debye shielding distance in a plasma and results are reported in case of a hydrogen plasma in presence of a transverse magnetic field varying from zero to 500 gauss. It is observed that the electron temperature decreases with the rising magnetic field and a similar variation is also observed with the increase of pressure. A quantitative theory has been developed and it is noted that results deduced from the theory are in satisfactory agreement with the experimental results specially for low values of magnetic field. The variation of Debye shielding distance with magnetic field and pressure is almost linear upto a pressure of 400 microns and the magnetic field of 300 gauss above which there is little variation either with pressure or with the magnetic field. A qualitative theory has been provided to explain the variation.

INTRODUCTION

The general method of determining the electron temperature of low density low temperature plasma is by means of probe method. There are various uncertainties in the interpretation of results obtained by the probe method and a new method has been developed in this laboratory (Sen & Ghosh 1966, Gupta & Mandal 1967) for the measurement of the plasma parameters. The method consists in measuring the radiofrequency conductivity of the ionised gas and study its variation with pressure. The theory indicates that the radiofrequency conductivity will gradually increase with pressure becoming a maximum at a certain pressure and then gradually diminish with the further rise of pressure. The real part of the radiofrequency conductivity is given assuming all the electrons are moving with the same velocity v by

$$\sigma_r = \frac{ne^2}{m} \cdot \frac{\nu_c}{\nu_c^2 + w^2} \tag{1}$$

and considering the variation of σ_r with pressure

$$(\sigma_r)_{\max}=\frac{ne^2}{m}\cdot\frac{1}{2w} \quad (1a)$$

where n is the number of electrons per and cc. ν_c is the collision frequency of the electron and w is the angular frequency of the applied radiofrequency field. From these two equations we get

$$\nu_c=w\left[\frac{(\sigma_r)_{\max}}{\sigma_r}\pm\sqrt{\frac{(\sigma_r)^2_{\max}}{(\sigma_r)^2}-1}\right] \quad (2)$$

From this relation it is possible to calculate the collision frequency of the electron at different pressures and $\nu_c=\frac{v_r P}{L}$ where L is the mean free path of the electron at a pressure of 1 mm. and v_r is the random velocity. L can be obtained from the relation $L=\frac{1}{A_0}$ where A_0 is the coefficient introduced by Townsend in his theory of electrical discharge, the values of A_0 have been given by Von Engal (1955) for various gases. From the derived value of v_r the electron temperature can be calculated from the relation $v_r=\sqrt{\frac{8KT_e}{m\pi}}$ where Te is the electron temperature and K the Boltzman constant. This method of measurement of the parameters of a discharge is actually free from many ambiguities because the probe used here does not distrub the general condition of the plasma. By applying a magnetic field either longitudianl or transverse, the change in the nature of the plasma parameters can also be investigated.

The Debye shielding distance λ_D of a plasma is given by

$$\lambda_D^2=\frac{KT_e}{4\pi ne^2}.$$

The electron density n can be obtained from the maximum value of σ_r because when σ_r is maximum

$$(\sigma_r)_{\max}=\frac{ne^2}{2mw}.$$

From these two measurements the Debye shielding distance can be obtained and its variation with pressure and magnetic field can be investigated.

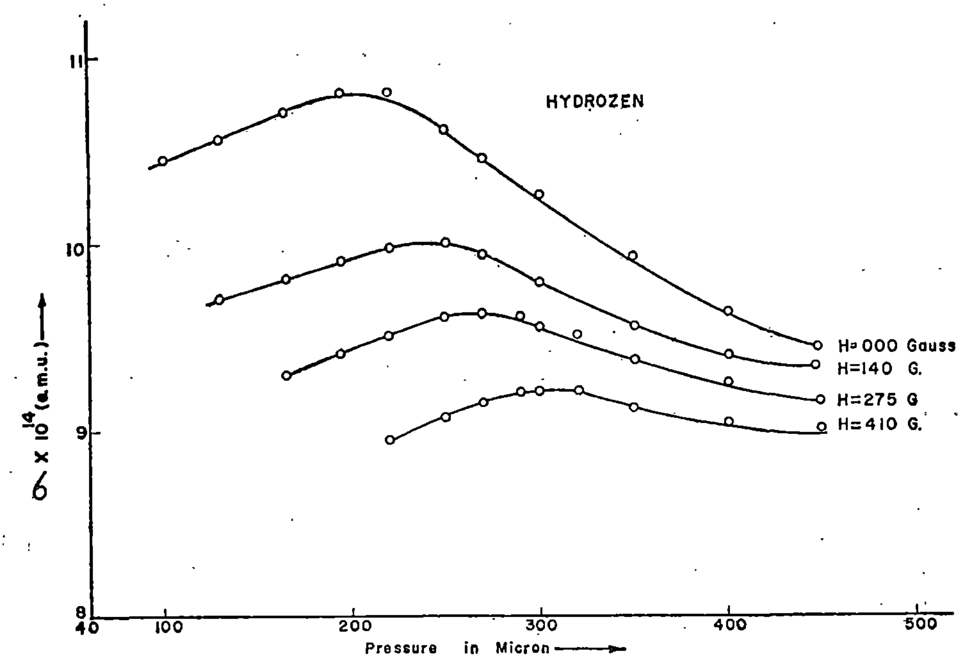
In all thermonuclear work, the presence of an external magnetic field is essential in some form for the confinement of the plasma. The plasma parameters are expected to be altered in presence of the magnetic field. To understand the nature of this variation and the effect it produces on the nature of the plasma itself, the present investigation has been undertaken and the paper reports the result in case of hydrogen plasma.

EXPERIMENTAL ARRANGEMENT

The method of measurement of the radio frequency conductivity has been described in detail in the earlier paper (Sen & Ghosh 1966). Hydrogen has been prepared by the electrolysis of a warm concentrated solution of barium hydroxide in a hard glass U tube fitted with two nickel electrodes. The gas is dried by passing over broken pieces of phosphorous pentoxide. The whole system was continuously evacuated for a number of days by an oil diffusion pump and the system flushed with the gas several times before measurements were taken. The pressure has been carefully measured with an Edward Penning Pirani Vacuum gauge. The effect of a steady transverse magnetic field on the plasma parameters has been investigated by placing the discharge tube well inside an electromagnet so that the lines of force are perpendicular to the length of the discharge tube and the magnetic field which has been measured by a clibrated fluxmeter. The frequency of the raido frequency voltage as provided by a tuned plate tuned grid oscillator was 10.2 Mc/sec and has been measured by a standard communication receiver. The discharge was excited by a transformer.

RESULTS AND DISCUSSION

The radiofrequency conductivity of ionised hydrogen has been measured with in the range of pressure of a few microns to 500 microns and a transverse magnetic field varying from 0 to 410 gauss which is perpendicular both the axis of the tube as well as to the direction of the radiofrequency field used to measure the conductivity. The results have been plotted in figure 1. It is observed that the conductivity gradually rises with



the increase of pressure and attaining a maximum value at a certain pressure gradually falls with the further increase of pressure in accordance with equation (1).

The condition for maximum conductivity has been obtained on the assumption that the electron density remains constant even if the pressure is changed. This assumption is justified as has been experimentally shown by Appleton & Chapman (1932) that the electron density is a function of the discharge current only and independent of pressure. In a recent communication it has been shown by Sen and Gupta (1967) from a theoretical argument that change of electron density is insignificant even if the pressure is increased by a factor of 20. The magnitude of the radiofrequency conductivity decreases in presence of the transverse magnetic field and the pressure at which the conductivity becomes a maximum gradually shifts to higher pressure with the rising magnetic field. The theoretical argument for the decrease of conductivity in presence of magnetic field has been advanced in a previous publication (Gupta & Mandal, 1967) where it was deduced that

$$(P_H)_{\max} = \frac{(\sigma_r)_{\max}}{(\sigma_{rH})_{\max}} \cdot P_{\max}. \tag{3}$$

where $P_{\max}$ is the pressure at which the conductivity becomes a maximum in absence of the magnetic field and $(P_H)_{\max}$ the pressure at which the conductivity becomes a maximum in presence of the magnetic field. The theoretical values calculated from equation (3) are entered in Table I. The above equation can be further modified when the variation of random velocity with magnetic field is taken into consideration; If v_r and v_{rH} are the random velocities in absence of magnetic field and in presence of magnetic field respectively

$$(\sigma_r)_{\max} = \frac{ne^2}{2m} \cdot \frac{L}{v_r} \text{ and } (\sigma_{rH})_{\max} = \frac{ne^2}{2m} \cdot \frac{L}{v_{rH}}$$

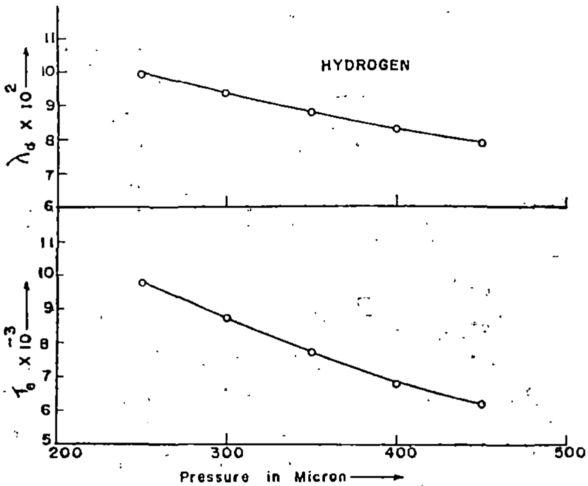
$$\text{hence } P_{\max} = \frac{v_r}{v_{rH}} \cdot \frac{(\sigma_r)_{\max}}{(\sigma_{rH})_{\max}}. \tag{4}$$

TABLE–I.

Mag field in gauss	($P_{\max}$) in micron from expt.	$(P_H)_{\max}$ from equation (3)	$(P_H)_{\max}$ from equation (4)
0	206		
140	245	227	253
275	270	236	285
410	305	246	325

The above theoretical deduction was based entirely upon the concept of equivalent pressure the validity of which becomes less and less as the value of the magnetic field increases. This can account to a certain extent the larger discrepency observed in the case of higher magentic fields. When however the variation of randomvelocity with magnetic field is taken into consideration, the theoretical results are in better agreement with experimental values as is evident from the values entered in the fourth column in Table I.

The electron temperature and the Debye shielding distance have been calculated and the variation of T_e and λ_D with pressure has been plotted in fig. 2. The corresponding variation with magnetic field has been plotted in fig. 3. It is observed as has been noted by Von Engel (1955) that the electron temperature gradually decreases with the increase of pressure. A qualitative explanation of this variation has been given by



Fig–2

FIG.–4

Sen and Ghosh (1963). Von Engel (1955) has shown that in case of a positive column

$$\frac{e^{x}}{x^{1/2}}=1\cdot2\times10^{7}.\ (CPR)^{2}$$

where C is a constant, and is equatl to $\left\{\frac{av_i^{1/2}}{K^{+}P}\right\}^{1/2}$ R is the radius of the tube, P the pressure, K^{+} the mobility of positive ions, "a" is the efficiency of ionization and $x=\frac{ev_i}{KT_e}$ then we get

$$\frac{e^{x}}{x^{1/2}}=\frac{1\cdot2\times10^{7}}{K^{+}}\ av_i^{1/2}\ R^2P=\alpha P.$$

where α is a constant for a particular gas and for a tube of radius R.

then $$\frac{dx}{dP}=\frac{1}{P\left(1-\frac{1}{2x}\right)}$$

and further $$\frac{dx}{dP}=\frac{eVi}{KT_e^2}\cdot\frac{dT_e}{dP}.$$

or $$\frac{dT_e}{dP}=\frac{KT_e^2/eVi.}{P\left(\frac{KT_e}{2eVi}-1\right)} \qquad (5).$$

In general T_e is of the order of 10^3 in case of molecular gases as is found in case of hydrogen and hence $\left(\frac{dT_e}{dP}\right)$ is negative, so the electron temperature diminishes with the increase of pressure.

To get an expression for the variation of electron temperature with magnetic field, it is to be noted that in presence of magnetic field the expression for equivalent pressure has to be taken and we get

$$P_H = P\left[1 + C_1 \frac{H^2}{P^2}\right]^{\frac{1}{2}}.$$

where C_1 is a constant and is given by $C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r}\right)^2$

where L is the mean free path of electron at a pressure of 1 mm and v_r is the random velocity.

Then we get when no magnetic field is present

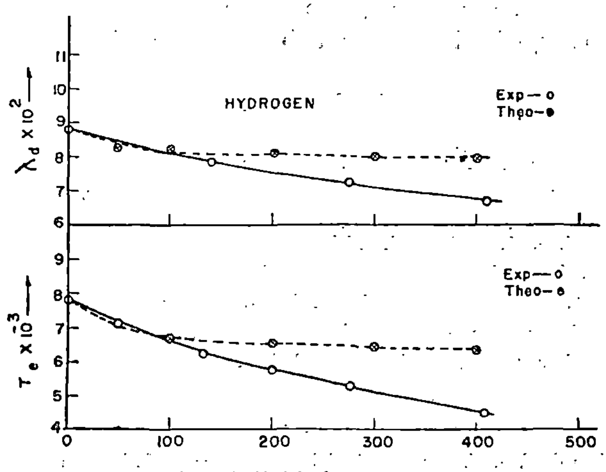
$$\frac{\epsilon^{eVi/KTe}}{[eVi/KT_e]^{1/2}} = \alpha P.$$

and when magnetic field present,

$$\frac{e^{eVi/K(Te)H}}{[eVi/K(Te)_H]^{\frac{1}{2}}} = \alpha P\left(1 + C_1 \cdot \frac{H^2}{P^2}\right)$$

From these two expressions we get, after making further calculation,

$$T_{eH} = T_e + \frac{2T_e^2 \log\left(\frac{1}{\sqrt{1 + C_1 H^2/p^2}}\right)}{T_e + \frac{2evi}{K}} \qquad (6)$$



Fig—3

As all the quantities in the right hand side of the expression is known, it is possible to calculate T_{eH} for different values of the magnetic field. The dotted curve in fig. 3 gives the variation of T_{eH} in accordance with equation (6). The general nature of the curve is almost of the same form as the experimental curve and the results are quite in agreement for low values of magnetic field. The discrepency observed for higher values of magnetic field can be attributed to the uncertainty in the value of the constant C_1 and to the fact that the variation of the random velocity with magnetic field has not been taken into consideration. The value of the constant $C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r}\right)$ has been calculated assuming that $L = \frac{1}{A_o}$ where A_o is the Townsend's coefficient in his theroy of electric discharge. But it has been pointed out by Townsend (1947) that this method of calculating the mean free path is not rigorous and in case of hydrogen he has given the value of L as lying between. 02 to.04 cm whereas in our calculation we have taken L as .2 cm. This introduces a certain element of uncertainty in the calculation. Further as has been pointed out earlier the concept of equivalent pressure loses its validity for high (H/P) values. Which also can account to a certain extent the divergence noted between the theoretical and experimental results for higher values of magnetic field.

The variation of λ_D, the Debye shielding distance with pressure and magnetic field shows that the variation is almost linear and decreases with the increase of pressure and magnetic field. The order of magnitude of λ_D is of the same order as has been calculated by Glasstone and Lovberg (1960) for large electron densities and high temperature plasmas. The mean free path of electron in hydrogen at a pressure of say 300μ is of the order of .6 cm which is much larger than λ_D measured here. When the pressure becomes large, the mean free path becomes comparable to λ_D and the variation with pressure becomes extremely small. The concept of equivalent pressure shows that pressure increases with magnetic field and hence the variation of λ_D with magnetic field can be explained on the same basis as the variation with pressure.

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