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Momentum transfer collision cross section for slow electrons in magnetic field from radio frequency conductivity measurements

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Momentum transfer collision cross section for slow electrons in hydrogen and oxygen in a transverse magnetic field varying from zero to 1850 gauss have been obtained by studying the variation of radio frequency conductivity of the ionized gas within the pressure range of a few microns to 6 torr. The momentum transfer cross section is higher than that without field for the same range of electron energies. The results have been discussed in the light of the experimental breakdown voltage measurements in these gases. It is further pointed out that the method is capable of providing accurate values for the electron density in these gases.

1. INTRODUCTION

In previous communications (Sen and Ghosh 1966, Gupta and Mandal 1967, Sen and Gupta 1969) it has been shown that the measurement of radio frequency conductivity of an ionised gas and its variation with pressure enables us to calculate the various parameters of the ionised gas such as the electron density, collision frequency and electron temperature. The measurement in presence of a magnetic field enables us to find the variation of electron temperature with magnetic field. The only effect of magnetic field that has been taken into consideration in the previous papers is the introduction of the concept of equivalent pressure and it has been found that the experimental results can be satisfactorily explained quantitatively for small values of (H/P) only where H is the magnetic field and P is the pressure; this is due to the fact that the equivalent pressure concept is valid only for small values of (H/P). The measurement of momentum transfer cross section of electrons for elastic scattering has been carried out in a large number of atomic and molecular gases for a wide range of electron energies by various standard methods such as swarm experiment, microwave after-glow method and the cyclotron resonance method and a comprehensive review of these methods and the analysis of the results obtained has been provided by Massy and Burhop (1969). The effect of a magnetic field on the collision cross section of electrons with atoms and molecules is important not only for understanding the nature of interaction of magnetic field with ionised gases but is absolutely necessary for explaining the phenomena of breakdown of gases in magnetic field. As the measurement of radio frequency conductivity of ionised gases and its variation with pressure and magnetic field enables us to calculate the electron density, collision frequency and electron temperature, so the same method is proposed to be adopted in the present investigation to calculate the momentum transfer cross section of electrons and its variation with electron energy (slow electrons) in a transverse magnetic field. A programme for the measurement of momentum transfer cross section in magnetic field, specially for low energy electrons has therefore been undertaken and the present paper reports the results in case of hydrogen and oxygen.

2. Theory of Calculation of Momentum Transfer Cross Section from R. F Conductivity Measurement

In the present experimental setup it is assumed that the discharge current is flowing along the x-axis, the radio frequency field used for measurement of r.f. conductivity along y-axis and the magnetic field along the z-axis. Then the equations of motion are

$$\frac{dv_y}{dt}+\nu v_y+\omega_B v_x=\frac{e}{m}E_0 e^{J\omega t}$$

where ν is the frequency for momentum transfer, ω is the frequency of the measuring radio frequency field and $\omega_B=(eH/m)$ the cyclotron frequency and similarly

$$\frac{dv_x}{dt}+\nu v_x-\omega_B v_y=0$$

then

$$v_y=\frac{eE_0(\nu+J\omega)e^{J\omega t}}{m[(\nu+J\omega)^2+\omega_B{}^2]}$$

and

$$v_x=\frac{\omega_B e E_0 e^{J\omega t}}{m[(\nu+J\omega)^2+\omega_B{}^2]}$$

Hence $\sigma_{(rf)H}$ which is the real part of r.f. conductivity in a direction perpendicular to the transverse magnetic field

$$\sigma_{(rf)H}=\frac{ne^2\nu\{\nu^2+\omega^2+\omega_B{}^2\}}{m\{(\omega^2-\nu^2-\omega_B)^2+4\omega^2\nu^2\}} \quad \ldots \quad (1)$$

which is the same expression as deduced previously by Appleton and Booihariwalla (1935) and later by Gilardini (1959). The energy of the electron in the magnetic field can be calculated and the energy

$$\epsilon=\frac{1}{2m}\cdot\frac{e^2E_0{}^2}{[\nu^2+\omega_B{}^2]} \quad \ldots \quad (2)$$

as the value of ω is smaller than either ν or ω_B by two orders of magnitude. Differentiating eq. (1) with respect to ν, which in effect means the change with respect to pressure, we get

$$\nu^6+\nu^4[\omega_B{}^2+\omega^2]-\nu^2[\omega^4+\omega_B{}^4-10\omega^2\omega_B{}^2]-(\omega^2-\omega_B{}^2)^2(\omega^2+\omega_B{}^2) = 0$$

As the magnetic field used in the experiment is of the order of a few kilogauss, and the measuring field has the frequency of a few megacycles i.e.

$$\omega_B \gg \omega$$

we get,

$$(\nu^4-\omega_B{}^4)(\nu^2+\omega_B{}^2) = 0$$

or

$$\nu = \omega_B.$$

In deriving the above expression it has been assumed that n, the electron density remains constant with the changes of pressure. To justify this it is noted that

$$i = ne\mu E = \frac{ne^2E}{m\nu} = \frac{ne^2E}{mbP}$$

where b is a constant. It is observed that with the change of pressure the discharge current changes but in our experiment we have kept the discharge current constant by changing the value of E. To test this point an experiment has been performed in which the pressure is varied and the corresponding value of E is noted so that the discharge current is kept constant and the results are plotted in figure 1. The linear relation observed between E and P indicated that for constant discharge current n the electron density remains constant with pressure.

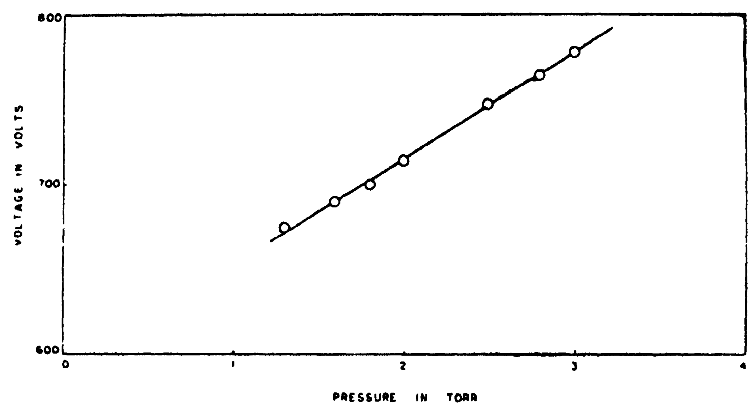

Fig. 1. Variation of applied voltage at different pressures to keep constant discharge current.

$\sigma_{(rf)H}$ will become a maximum when $\nu = \omega_B$ from which the collision frequency at the particular pressure can be calculated and as $\nu_c = v_r/\lambda_e = v_rP/L$

we get

$$\frac{v_rP_{max}}{L} = \frac{eH}{m}$$

or

$$\frac{H}{P_{max}} = \text{constant},$$

where P_{max} is the pressure at which the radio frequency conductivity becomes a maximum when the magnetic field H is applied.

As
$$\nu = N\sigma_c \sqrt{\frac{8kT_e}{m\pi}} \qquad \ldots \quad (3)$$

where N is the number of molecules per c.c. at the pressure considered, σ_c is the momentum transfer cross section, T_e is the electron temperature, m is the mass of the electron and K is the Boltzman constant. The electron temperature has been measured by single probe method and its variation with magnetic field has been found to satisfy the theoretical deduction (Sen, Das and Gupta 1972) for small (H/P) values namely

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

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

where L is the mean free path of the electron in the gas at one torr. The value of C_1 has been found to be 5.62×10^{-5} in close agreement with that obtained by Blevin and Haydon (1958) and that of oxygen is 17.14×10^{-5}.

Hence from eq. (3) σ_c the momentum transfer cross section in presence of magnetic field is given by

$$\sigma_c = \frac{(\nu/P)}{\left(\frac{N}{P}\right)\left(\frac{8KT_e}{m\pi}\right)^{\frac{1}{2}}\left[1+C_1\frac{H^2}{P^2}\right]^{1/4}} \qquad \ldots \quad (4)$$

3. Experimental Arrangement

The present investigation reports the results regarding the variation of r.f. conductivity with pressure in a transverse magnetic field in case of hydrogen and oxygen. The measuring field has a frequency of 2.45 MHz and the variation of pressure is in the millimeter range and magnetic field employed is 1 kilogauss to 2 kilogauss so that the assumption $\omega \ll \omega_B$ is justified.

The method of measurement is the same as has been used in the previous paper (Sen and Ghosh 1966); hydrogen and oxygen have been prepared by the electrolysis of a saturated solution of warm barium hydroxide and dried by potassium hydroxide and phosphorous pentoxide.

The pressure has been accurately measured by a calibrated MacLeod gauge and the magnetic field by a calibrated gauss meter.

4. Results and Discussion

The variation of r.f. conductivity with pressure in transverse magnetic field 1150G, 1350G and 1850G in case of hydrogen and oxygen have been plotted in figures 2 and 3. In each case it is observed that the r.f. conductivity becomes a maximum at a certain pressure and the pressure at which the conductivity becomes a maximum always shifts towards the higher pressure with the increase of magnetic field and the absolute value of conductivity diminishes with magmetic field for all values of pressure. The experimental results have been entered in table 1.

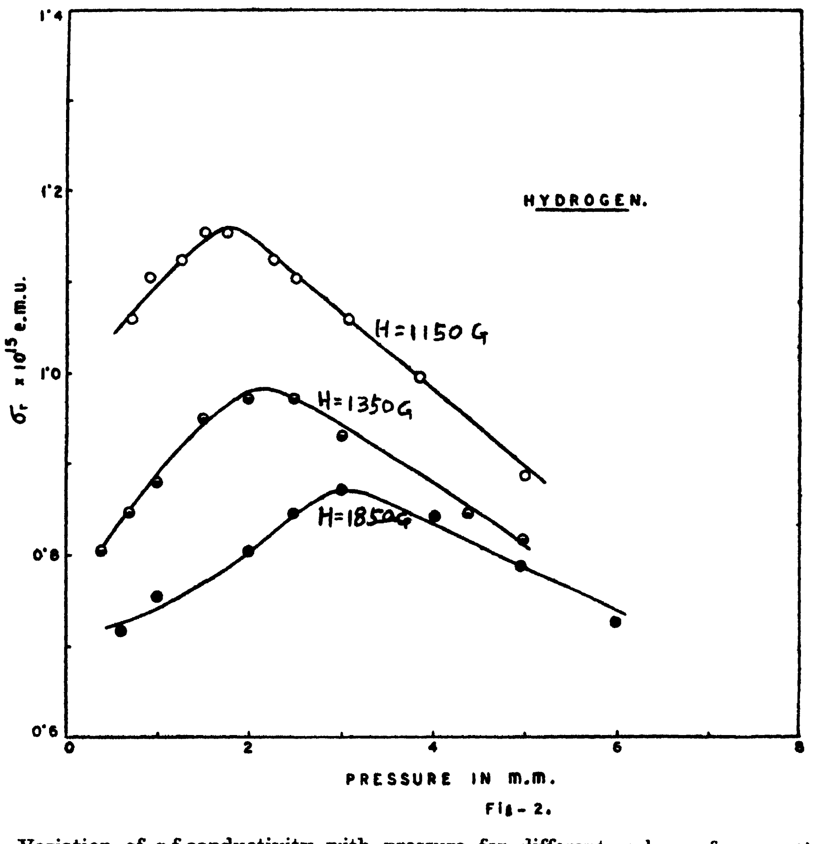

Fig. 2. Variation of r.f.conductivity with pressure for different values of magnetic field; Hydrogen.

It is evident from column VI that the theoretical deduction H/P_{max} = constant for maximum conductivity is well satisfied. From the expression $\nu = \omega_B$ for maximum $\sigma_{(rf)H}$ the value of ν can be obtained and the results are entered in the fifth column in table 1. We have then calculated utilizing eq. (4) the values of momentum transfer cross section for various values of magnetic field ranging

Table 1. Frequency of measurement 2.45 MHz

Gas	Magnetic field in gauss	$(P_H)_{max}$ in mm	$(\sigma_{rf})_{max}$ $\times 10^{+15}$ e.m.u.	ν	H/P_{max}	n
Hydrogen	1150	1.85	1.16	$.3222 \times 10^{10}$	621.6	1.668×10^{8}
	1350	2.15	.985	$.3791 \times 10^{10}$	626.9	1.662×10^{8}
	1850	3.05	.72	$.5184 \times 10^{10}$	618.0	1.665×10^{8}
Oxygen	1150	.9	1.19	$.3222 \times 10^{10}$	1277	1.693×10^{8}
	1350	1.1	.965	$.3791 \times 10^{10}$	1228	1.629×10^{8}
	1850	1.5	.70	$.5184 \times 10^{10}$	1236	1.619×10^{8}

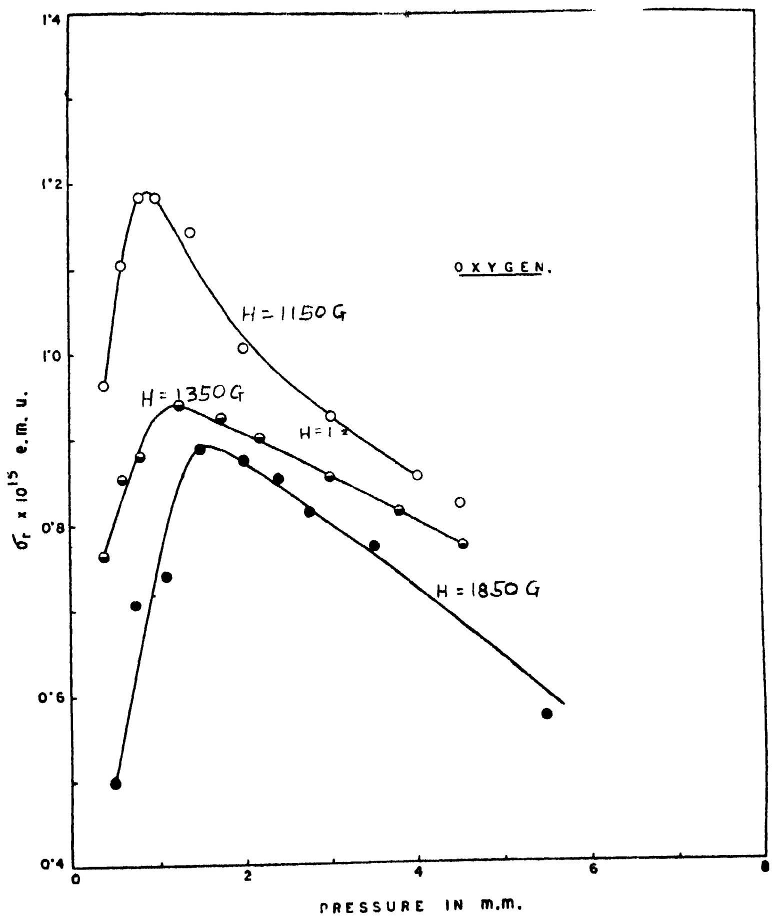

Fig. 3. Variation of r.f. conductivity with pressure for different values of magnetic field; Oxygen.

from 50 to 1850 gauss for corresponding energies calculated from eq. (4) for both hydrogen and oxygen and the results are plotted in figure 4; for comparison, the values of momentum transfer cross section without magnetic field by previous workers are also shown in the figure. It is noted that for range of electron energies investigated here the momentum transfer cross section when magnetic field is present is always greater than in the absence of the field with a tendency to increase for higher electron energies. The variation of momentum transfer cross section with electron energy without the magnetic field has been explained by Forst and Phelps (1962) and the experimental results are found to be in good agreement. In the said deduction the distribution of electron energies has been assumed to be Maxwellian but as no adequate energy distribution function has been found for electrons in a magnetic field, no attempt has been made here to deduce any quantitative expression for the momentum transfer cross section in magnetic field. The increase of momentum transfer cross section in presence of magnetic field indicates more loss of energy by the electrons and consequently higher breakdown voltages will be required in presence of magnetic field. The results are corroborated by breakdown field measurements.

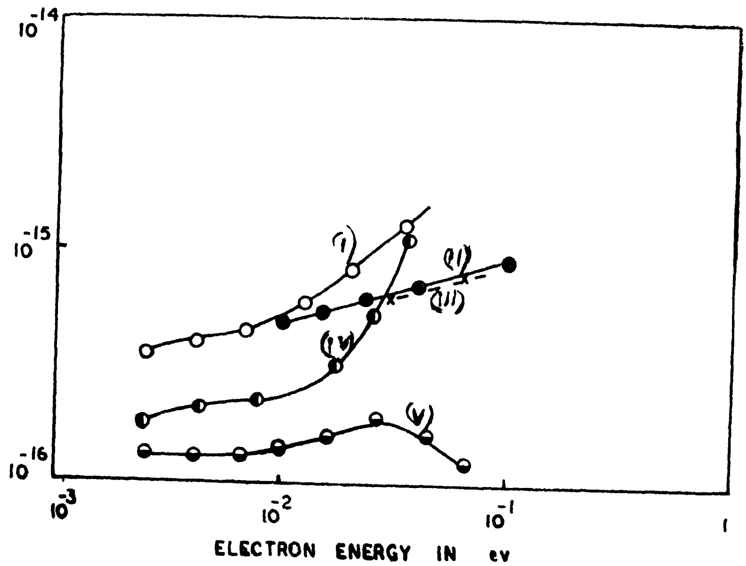

Fig. 4. Variation of momentum transfer cross section with electron energy.

These measurements also provide us with a method of calculating the electron density; when $\nu = \omega_B$, we have

$$\sigma_{(rf)max} = \frac{ne^2}{2m\omega_B}$$

The value of n calculated by this method has been entered in the seventh column of table 1. The near consistency of the values obtained is due to the fact that the discharge current has been kept constant for the magnetic fields studied here. The results are also corroborated by probe measurements.

It is thus observed that the measurement of the radio frequency conductivity of an ionised gas and its variation with pressure in a magnetic field enables us to calculate the plasma parameters such as electron density and collision frequency. This measurement combined with measurement of electron temperature enables us to calculate the momentum transfer cross section and its variation with electron energy.

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