MEASURING THE INTENSITY OF MOLECULAR BEAMS

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Abstract

A Pirani gauge sensitive to pressure changes of the order of 10^{-8} mm of mercury has been developed and used to measure the intensity of molecular beams defined by two circular openings, one 0.4 and the other 0.6 mm in diameter placed 25 mm apart. The gauge is situated 40 mm from the last opening. A beam of air gives a galvanometer deflection equivalent to 600 cm with a pressure of 0.5 mm of mercury behind the first opening. Under similar conditions H_2 produces a deflection of 1800 cm. The galvanometer sensitivity is 11.6 mm per microvolt. The time lag of the gauge is less than the period of the galvanometer (7 seconds). The limits within which the beam-forming system may be expected to give a Maxwellian distribution of velocities are discussed. The final pressure in the gauge due to a given beam depends upon the dimensions of the gauge opening as kinetic theory predicts. The reduction in intensity of a beam of H_2 by collision with either air or H_2 present in the experimental chamber at various pressures has been measured. The data show that the gauge may be used to measure mean free paths and to obtain more detailed information than has previously been possible as to the probability of scattering through various angles by collision.

Introduction

IN RECENT years the angular distribution of a beam of electrons after scattering by a gas has been studied in detail. No doubt the equally interesting and important problem of the scattering of a beam of molecules or atoms has been neglected because there has not been available a method of measuring the intensity of such beams. The reflection of atoms from a crystal may also be studied advantageously by the aid of a gauge which will measure accurately the intensity of molecular beams. In order to be most efficient in this connection the gauge should have a small internal volume so that it will respond rapidly to changes in beam intensity and small overall dimensions so that it may be placed entirely within the vacuum system and controlled magnetically if this seems desirable. The experiments described in this paper were undertaken to devise such a gauge. Some very notable advances have already been made in this field.[1]

Apparatus

A Pirani gauge, discussed at length in the preceeding paper, was constructed with a small opening in one side (Fig. 1) so that the pressure inside would be affected when the opening was moved into the path of a beam of molecules. By measuring the pressure change inside the gauge a measure of the beam intensity is obtained.

[1] F. Knauer and O. Stern, Zeits. f. Physik **53**, 766 (1929).

The ends of the gauge must be fitted carefully as experience has shown that arrangements which appear to fit well mechanically may leak considerably. The gauge has an internal volume of 0.5 cc so that it responds quickly to changes in beam intensity. The time required for the pressure in the gauge to reach equilibrium is normally less than the period of the galvanometer (7 sec.).

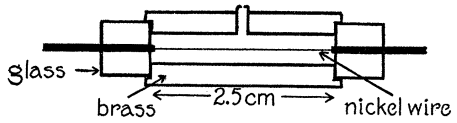

Fig. 1. The Pirani gauge applied to the measurement of molecular beams.

The extreme shortening of the wire seems to have no disadvantage other than decreasing the sensitivity of the gauge. The conduction of heat from the filament to the leads which would, of course, become more troublesome as the length of the filament is decreased has not interfered with the action of the gauge to an appreciable extent.

The apparatus which forms the molecular beam used in the investigation of the characteristics of the gauge consists of 3 circular openings (Fig. 2), the first of which is 0.4 mm in diameter, the second is 0.7 mm in diameter and is situated 1.75 mm from the first, and the third is 0.6 mm in diameter and situated 25 mm from the first. The second opening does not serve to define the beam but merely to prevent the spreading of the comparatively high

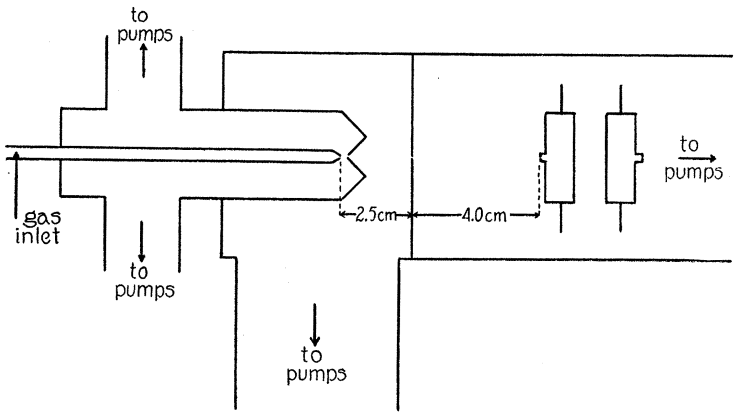

Fig. 2. The construction of the apparatus for the formation of molecular beams.

pressure in B throughout the entire distance between the first and last opening. It is made slightly larger than the other openings in order to eliminate any difficulties there might be in correct alignment. This precaution is hardly necessary here but might be in case very narrow slits were used to form the beam. The third opening was made larger than the first in order to secure a beam in which the width of the maximum intensity portion of the beam would be equal to the diameter of the largest gauge opening used. It is, of

course, obvious that the last opening could be reduced to the size of the first (0.4 mm) thus decreasing the angular divergence of the beam without decreasing its maximum intensity.

The distance between the first two openings of the beam system was adjusted experimentally to give the correct relative pressures in B and C for maximum efficiency. This distance depends upon the relative pumping speeds at B and C which are 4 and 18 liters of air per second, respectively. A change of 0.1 mm in this distance will produce an appreciable reduction in the maximum beam intensity which can be obtained.

A beam system consisting of two openings was not satisfactory for producing beams of high intensity. The impedance inherently existent in an apparatus when two slits are placed near each other makes it difficult to reduce the pressure between them sufficiently for the formation of an intense beam even if the necessary pumping speed is available.

The position of the gauge used in measuring the beam is shown in Fig. 2. It is arranged so that it may be rotated about the last opening of the beam system. The compensating gauge which is placed nearby forms the arm of the bridge adjacent to the main gauge and maintains the bridge balance for general changes in pressure as well as changes in temperature in the experimental chamber. Where high sensitivity is necessary it is advisable to place both gauges in a common metal container or form both from the same piece of metal.

Procedure

The final pressure in the gauge due to a given beam will depend upon the size and shape of the opening into the gauge. The most advantageous form of opening may be predicted by a consideration of Knudsen's law of molecular flow.

Since the pressure in the gauge is always such that the mean free path is large compared to the dimensions of the container, it is evident that the gauge opening, regardless of its length or diameter, will offer no impedance to the entrance of the molecules of the beam if the apparatus is arranged so that they do not strike the walls of the opening. Hence the pressure inside the gauge will build up to such a value that the quantity of gas which flows out through the gauge opening is equal to that which enters it from the beam. The quantity of gas Q measured in cm^3 at 1 bar flowing through a tube of length L and radius r per second is given by Knudsen[2] as

$$Q = \frac{1}{\rho_1^{1/2}} \frac{p_1 - p_2}{W_1 + W_2} \tag{1}$$

where ρ_1 is the density of the gas at 1 bar and at the temperature of the apparatus and the partial impedances W_1 and W_2 are given by

$$W_1 = \frac{(2\pi)^{1/2}}{\pi r^2} \tag{2}$$

and

[2] M. Knudsen, Ann. d. Physik **28**, 75 and **28**, 999 (1909).

$$W_2 = \frac{3L}{4(2\pi)^{1/2}r^3}. \tag{3}$$

Assuming that the molecules emerge from the initial opening of the beam system with a cosine distribution, the amount of gas entering the gauge and also the amount leaving it per second when equilibrium is established is

$$\frac{Q'r^2}{D^2}$$

where Q' is the quantity of gas used in forming the beam, r is the radius of the gauge opening, and D the distance from the initial beam opening to the gauge opening. Substituting the value of Q given above and the values of W_1 and W_2 from Eqs. (2) and (3) in Eq. (1) we obtain upon solving for (p_1-p_2) the quantity actually measured by the gauge

$$p_1 - p_2 \equiv (\rho_1)^{1/2}\frac{Q'}{D^2}\left(\frac{2^{1/2}}{\pi^{1/2}} + \frac{3L}{4(2\pi)^{1/2}r}\right). \tag{4}$$

Hence if the gauge opening is a hole in a thin wall the equilibrium pressure is independent of the radius. If, however, the gauge opening is long as compared to its radius the equilibrium pressure is proportional to its length and inversely proportional to its radius. The effect of the dimensions of the gauge opening upon the sensitivity of the gauge is shown by Table I. The

TABLE I. *The effect of the dimensions of the gauge opening upon the sensitivity of the gauge.*

Dimensions of gauge openings (mm)		Relative deflection	
Length	Diameter	Computed	Observed
12	0.37	18	18
12	0.5	11.3	11.7
12	1.0	6	6.2
4	0.37	6	6
0	0.1	0.6	1

calculated values of the relative sensitivity are obtained from Eq. (4). The agreement is well within the limits to which the dimensions were actually known except in the case of the 0.1 mm hole. Here the disagreement may be explained by the reasonable assumption that the wall has a thickness of 0.08 mm.

For many purposes it is desirable that the molecular beam under consideration have a Maxwellian distribution of velocities. Previous investigators[3,4] have shown that a beam possesses a Maxwellian distribution of velocities if the pressure behind the first opening is such that the mean free path is several times the diameter of the opening and the pressure along the path of the beam is such that the effect of collisions may be neglected. Fig. 3 shows that the latter condition is easily satisfied. As long as the intensity of the beam is proportional to the amount of gas forming it, collisions have not

[3] J. A. Eldridge, Phys. Rev. **30,** 931 (1927).
[4] I. F. Zartman, Phys. Rev. **37,** 383 (1931).

become a factor. Further evidence of the same nature was obtained by plotting beams such as shown in Fig. 4 over a wide range of intensity. In the case of both air and H_2, beams were plotted from the first point shown in Fig. 3 to

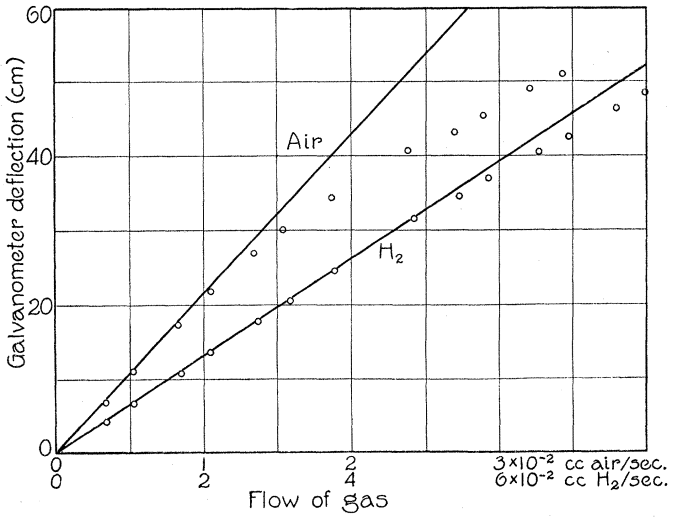

Fig. 3. Volume of gas forming beam plotted against beam intensity. Galvanometer sensitivity, for air 1/10, for H_2 1/20.

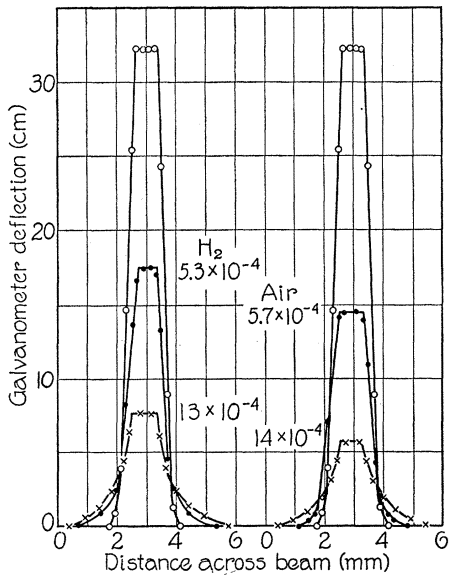

Fig. 4. The spreading of a beam of H_2 with increasing pressures of air and H_2 in its path.

the point where the curves first leave the straight lines. In neither case was there an appreciable spreading of the beam such as would result from collisions taking place between the openings.

The limitation placed upon the beam intensity by the first condition mentioned above may be obtained from Table II. A comparison of the values of the mean free path at A given in this table with the diameter of the opening (0.4 mm) show that the requirement of low pressure behind the first opening, rather than the speed of the pumps, is the limiting factor in the beam intensity which can be obtained if a Maxwellian distribution of velocities is desired. Table II also contains the values of the pressures for the various compartments of the beam system.

TABLE II. *Pressures at various points in the beam system. (mm of mercury).*

	Points from figure 3	A*	B	C	Mean free path at A
Air	1	0.15**	3.2×10^{-4}	1.6×10^{-5}	0.50 mm***
	2	0.26	6.3	3.6	0.30
	4	0.53	13.	3.6	0.14
	8	1.22	27.	3.6	0.07
	12	1.72	38.	3.6	0.05
H_2	1	0.08	2.6×10^{-4}	1.6×10^{-5}	2.0
	2	0.14	4.0	1.6	1.0
	4	0.28	9.0	2.5	0.54
	6	0.42	14	2.5	0.36
	8	0.63	19	3.6	0.24
	11	0.87	28	3.6	0.18
	14	1.08	33	3.6	0.15

The pressure in the experimental chamber is in all cases better than 10^{-6} mm Hg.
* See Fig. 2.
** These values were computed.
*** Mean free path for spherical model assuming air to be composed of oxygen and nitrogen[5].

The equilibrium pressure in the gauge resulting from a given beam may be computed by the application of Eq. (4) and from the calibration constant of the gauge. The comparison of these two values is of interest. The physical constants and the dimensions of the apparatus appearing in Eq. (4) have the following values: $\rho_1=1.16\times10^{-9}$ (air); $D=6$ cm;[6] $L=1.2$ cm; and $r=0.0185$ cm. The quantity of gas Q' used in forming the beam in the case of the third point on the air curve in Fig. 3 is 8.1×10^{-3} cm^3 at atmospheric pressure or 8.1×10^{3} cm^3 at 1 bar. Substituting these values $p_1-p_2=0.154$ bars or 1.15×10^{-4} mm of mercury. Computing the excess pressure in the gauge from the calibration constant (5.8×10^{-8} mm of mercury per mm galvanometer deflection) and the deflection we obtain $p_1-p_2=1.03\times10^{-4}$ mm of mercury.

The error is approximately 10 percent and is within the limits of accuracy to which the Pirani gauge had been calibrated by comparison with a McLeod gauge.

Similar computations for H_2 yield values of the observed pressures which are approximately 30 percent greater than kinetic theory predicts.

With the aid of a gauge of the type discussed above it should be possible to obtain more detailed information about the nature of molecular collisions.

[5] Dushman, Gen. Elec. Rev. 18, 952, 1042, 1159 (1915).
[6] This value is slightly less than the one given in Fig. 2 because of the increased length of the gauge opening.

The following brief discussion of the decrease in intensity and the scattering of molecular beams by increased pressure in the gauge chamber shows some of the possibilities of the gauge.

The scattering of a beam of H_2 in the experimental chamber is shown in Fig. 4. The beam travels 4 cm in this chamber before striking the gauge opening. In order to eliminate any directional preference of the gauge to the incident molecules a 0.1 mm hole in a thin wall formed the opening into the gauge. This is desirable for as the gauge is turned to one side of the main beam a long opening will permit scattered molecules to enter the gauge with zero impedance only if they are scattered from the portion of the beam which is in line with the gauge opening and at the proper angle to strike that opening. The hole in the thin wall will, on the other hand, permit the entrance of molecules scattered from any point along the beam. The long opening might be used advantageously for a detailed study of the probability of various scattering angles.

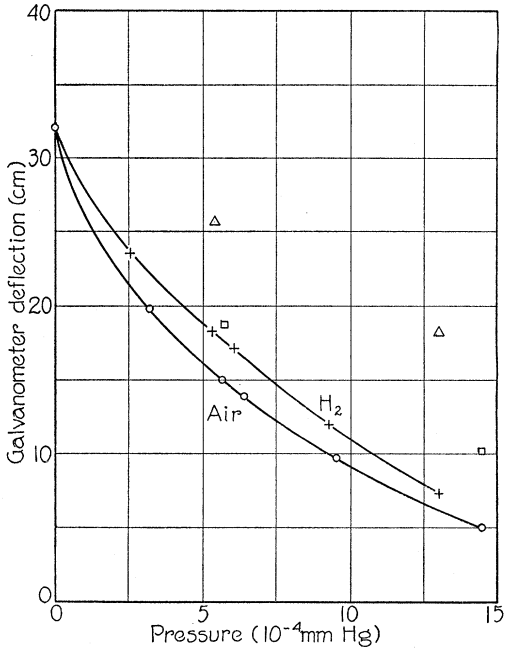

Fig. 5. Beam intensity as a function of the pressure in the experimental chamber.

Since the beams shown in Fig. 4 are circular and the readings were taken across a diameter, the actual areas covered by the beams are proportional to the square of the width of the curve.

In Fig. 5 the curves represent the decrease in the maximum intensity of the beams with increasing pressures of air and H_2 in the experimental chamber. The value of the mean free path of H_2 in H_2 as determined from this figure is 3.8 cm at a pressure of 10^{-3} mm of mercury. A comparison of this decrease in maximum intensity and the decrease in the percentage of the

molecules of the original beam which can be found near the center of the beam is of interest. The relative number of molecules found within this limit can be determined by a comparison of the area intensity summations of the curves of Fig. 4. These summations are represented in Fig. 5 by the triangles for H_2 and the squares for air, where the summation of the original beam is represented by 32 and the summations of the scattered beams are relative to the original. For example with an H_2 pressure of 5.3×10^{-4} mm of mercury in the experimental chamber the maximum intensity of the H_2 beam is reduced to 54 percent of its original value while 80 percent of the original number of molecules can be found near the center of the beam. With a slightly higher pressure of air the maximum beam intensity is reduced to 46 percent and 57 percent of the molecules can be found near the center of the beam. This indicates as would be expected that there is greater probability of large angle scattering in air than in H_2.

Conclusion

The only difficulty encountered in the use of these gauges is the elimination of the zero drift. This drift seems to arise principally from unequal evolution of gas from the walls of the beam and compensating gauges, and from changes in room temperature. The latter effect becomes less the more nearly the two gauges are alike but it seems impossible to eliminate it entirely. The drift due to unequal outgassing is, of course, increased with increase in the impedance of the opening. In any case it may be eliminated to a great extent by baking out the gauges so that it is possible to reduce the drift of the galvanometer at maximum sensitivity to one cm in fifteen minutes.

The data given in Fig. 2 and Table II show that a beam of air formed by a pressure of 0.5 mm of mercury behind the first opening of the beam system produces a galvanometer deflection equivalent to 200 cm. H_2 under similiar conditions produces a deflection of 600 cm. Since the above results were obtained, gauges have been constructed with three times the sensitivity of those used in taking the above readings merely by an improved method of flattening the wire and an increase in the length of the wire. Hence we may say that it is possible to form beams of air and H_2 which have approximately a Maxwellian distribution of velocities and produce galvanometer deflections of 600 and 1800 cm, respectively. Allowing a large margin of safety, we may assume that the galvanometer deflections are accurate to 0.5 mm. Then the relative intensity of beams of air may be determined with an accuracy of 0.08 percent. Likewise the intensity of a beam of H_2 may be determined to an accuracy of 0.03 percent. This sensitivity is ample for the determination of the mean free path of gases, for the investigation of the probability of various scattering angles resulting from collision, and for a study of the reflection of atoms from crystals. A scattered beam of H_2 with an intensity of 1 percent of the initial beam may be measured with an accuracy of 3 percent.