STUDIES WITH THE IONIZATION GAUGE.

I. CONSTRUCTION AND METHOD OF CALIBRATION.

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SYNOPSIS.

An Ionization Gauge for Measuring Very Low Pressures.—This gauge is the result of an attempt to develop a more convenient instrument than those previously available. It is based upon the fact that the positive ionization produced by a given stream of electrons varies with the gas pressure. By adopting a *construction* similar to that used for low power pliotrons, erratic effects due to the charging up of the glass walls were avoided and, with a constant electron emission, a linear relation was obtained between ionization current and pressure down to the lowest pressure actually obtaiued, about 10^{-3} bar. For pressures above 10^{-1} bar the *calibration* was carried out by comparison with a McLeod gauge; but for lower pressures a method was used which involves an application of Knudsen's laws of flow. *Characteristic curves* showing the effect of varying the positive voltage and the electron emission on the ionization current are given. The *low limit of pressure* measurable with such a gauge is fixed only by the sensitivity of the galvanometer used to measure the ionization current. With an ordinary sensitive galvanometer, pressures as low as 10^{-4} bar can readily be determined.

INTRODUCTION.

DURING the past few years, as the technique of high vacuum production has improved, there have of necessity been developed a number of methods of measuring these extremely low gas pressures. Of these methods, the absolute gauge devised by M. Knudsen[1] and the molecular gauge suggested by I. Langmuir[2] have been used fairly extensively. In both types, however, the difficulties of construction and operation are such as to make their use very inconvenient.

Some time ago Dr. Hull suggested to the writers that a gauge might be devised based on the measurement of the amount of positive ionization produced by an electron stream. After some preliminary experiments had been carried out with a gauge based on this suggestion, a paper on the same subject appeared by O. E. Buckley.[3]

More recently Misamichi So[4] has also described the results of an investigation carried out with a gauge constructed on the same principle.

[1] Ann. Phys., *32* (1910), and *44*, 525 (1914).

[2] PHYS. REV., 1, 337 (1913), and also S. Dushman, PHYS. REV., *5*, 212 (1915). This paper contains a brief review of the different types of gauges that have been used for measuring very low gas pressures.

[3] Proc. National Acad. of Sciences, *2*, 683 (1916).

[4] Proc. Physico-Mathem. Soc. Japan, I., 76 (1919).

The manometer consists of three electrodes sealed in a glass bulb which serve as cathode, anode and collector of positive ions respectively. The cathode may be either an incandescent tungsten filament or Wehnelt cathode. Under the influence of the accelerating field due to the anode the electrons ionize the gas molecules with which they collide and the positive ions thus produced are collected by the third electrode which is negatively charged with respect to the more negative terminal of the cathode.

According to Buckley, "The exact forms of the electrodes are not of great importance. The collector is preferrably situated between the other two electrodes and of such form as not to entirely block the electron current to the anode." Preliminary experiments were carried out with a simple gauge consisting of three V-shaped filaments placed in parallel planes. (A similar construction has also been used by So.) On trial, it was found, however, that with this construction it was not always possible to obtain a linear relation between ionization current and pressure. Also, there was trouble due to the charging up of the glass walls. In the present paper the authors describe a type of gauge which gives a linear relation between pressure and ionization current and which shows no erratic effects from charging up of the glass walls.

DESCRIPTION OF GAUGE.

Of the many types of construction tested, that shown in Fig. 1 has been found to have the best characteristics for measuring small pressures.

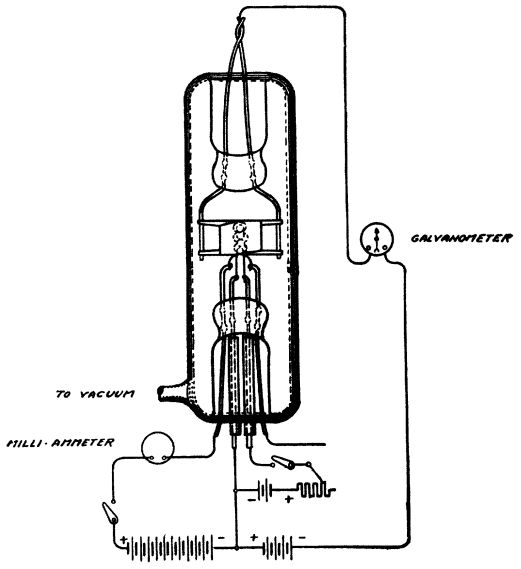

Fig. 1.

It consists of two tungsten filaments, each wound in the form of a double spiral and mounted co-axially on a four lead stem which is sealed into the lower end of a glass tube about 4 cms. in diameter and 12 cms. long. The inner spiral is made of 5 turns of 0.125 mm. tungsten wire wound on a 2.25 mm. mandrel. The outer spiral is made of 3 turns of 0.125 mm. tungsten wire wound on a 3.65 mm. mandrel. Surrounding the spirals is a molybdenum cylinder about 12 mm. in diameter and 12 mm. long, which is supported on a two-lead stem at the upper end of the tube.

PRELIMINARY TREATMENT OF GAUGE.

Before using the gauge for any measurements it is absolutely essential that all water vapor absorbed on the glass walls and gases occluded in the metal parts be completely eliminated. The usual practice adopted by the writers in the treatment of the gauge preliminary to calibration is as follows: After starting the exhaust with a Langmuir condensation pump, the gauge is heated in an oven to 360° C. for at least one hour. This removes practically all the water vapor. In order to free the molybdenum cylinder of gas, it is made anode with respect to the outer spiral which is used as hot cathode. The temperature of the latter is adjusted by varying the current through it until the electron emission is about 100 milliamps. With an anode voltage of 250 volts this corresponds to an energy input of 25 watts (5.5 watt/cm.^{2} approx. anode area) and is sufficient to raise the temperature of the cylinder to a red heat. The gas liberated in consequence of this electronic bombardment causes blue glow in the gauge, which disappears as the exhaust proceeds. The electron emission is then gradually increased until finally it reaches about 400 milliamps., corresponding to 100 watts energy input (22 watts/cm.^{2}). With this amount of energy the cylinder runs at a bright red heat (about 1900° K.) and the elimination of gas occurs very rapidly. Momentarily the energy input may be increased to 150 watts; but there is serious danger, under these conditions, of melting the cylinder locally. After this treatment the anode is usually quite bright and all traces of oxide on its surface have disappeared.

To clean the leads supporting the spirals, one spiral is used as hot cathode to bombard the other which is used as anode. With an energy input of 15 to 20 watts, the leads are heated to a bright red heat and gas is removed very rapidly. It is of the utmost importance to have the leads free from gas before taking any measurements with the gauge as otherwise there will be a continual evolution of gas during the experiment.

CHARACTERISTICS OF GAUGE.

The measurements which are discussed in this paper were carried out with pure argon, the gas being introduced into the gauge after it had been exhausted by the above method to a good vacuum. In all cases, the residual gas pressure (as shown by the ionization current) was less than 0.1 per cent. of the pressure of the gas introduced. As the ionization gauge reads *total gas pressure*, extra care was taken to eliminate mercury vapor and other condensible gases from the gauge when introducing the argon.

The positive ionization current will in general be a function of the gas pressure, electron current, anode voltage, and collector (negative) voltage. A number of characteristics were therefore taken to determine the effect of each of these variables. The arrangement of the electrodes for this set of measurements was as follows: The inner spiral was the cathode, the outer spiral was the anode and the cylinder was the collector of positive ions.

It was observed that varying the collector voltage (only) from 0 to -22 volts (with respect to the negative end of the cathode spiral) caused only a slight increase (about 10 per cent.) in the ionization current. However, in order to eliminate absolutely the possibility of any electrons reaching the negative electrode, the potential of the latter has been maintained at -22 in all the measurements with the gauge.

Fig. 2 shows the relation between anode potential and ionization cur-

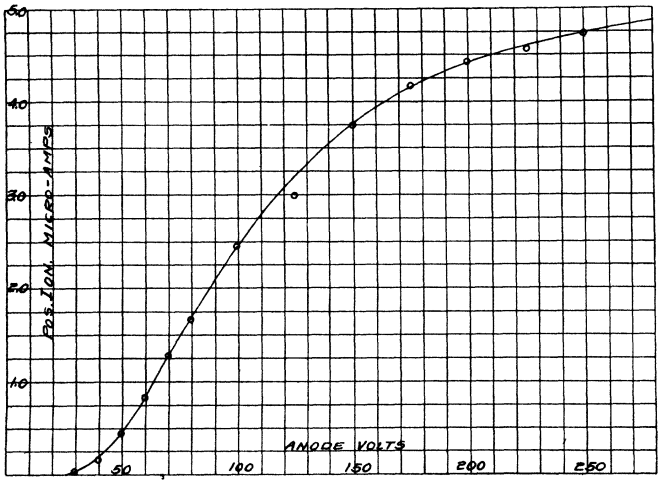

Fig. 2.

Argon at 1.85 bars.
Anode milli-amps = 0.5.
Collector volts = -22.

rent at a pressure of 1.85 bars argon and with a constant electron current of 5×10^{-4} amps. It will be observed that just above 50 or 60 volts, the ionization current increases at first very rapidly and then more slowly, as the voltage is raised still higher. This portion of the curve is found to satisfy an empirical relation of the form

$$i = i_0 (1 - e^{-B(V-V_0)}),$$

where i = ionization current, V = anode volts i_0, B and V_0 are constants.

Fig. 3 shows the effect of varying the electron emission. The pressure

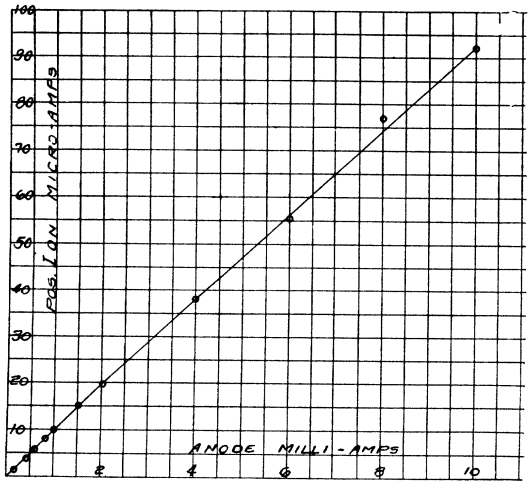

Fig. 3.

Argon at 1.85 bars.
Anode volts = 250.
Collector volts = − 22.

in this case was again 1.85 bar, and the anode potential, 250 volts. It will be observed that there is a deviation from the linear relation which might be expected to exist between ionization current and electron current. The reason for this is probably to be explained by the following considerations: With the arrangement of electrodes indicated above electrons passing from the inner spiral to the outer one do not take the shortest path. Most of them pass beyond the anode, into the space between the latter and the cylinder until the potential gradient due to the latter becomes negative and thus causes the return of the electrons towards the outer spiral. The amount of positive ionization depends both on the number of electrons and the length of path traversed by these electrons between cathode and anode. It is evident, however, that as the electron current increases the average length

of this path is decreased because of the space charge of the electrons between the anode and collecting electrode, and consequently the relative ionization is also decreased.

From the characteristics just described, the following conditions were chosen: 250 volts on the anode, − 22 volts on the collecting cylinder and a maximum electron current of 20 milliamperes. The sensitivity of the gauge is controlled by the electron current but it is found that the two values 0.5 and 20 milli-amperes respectively, cover a range sufficiently broad for all practical purposes (50 to 0.0001 bar).

CALIBRATION OF IONIZATION GAUGE.

The first calibration of the ionization gauge was made by checking directly against a fine McLeod gauge. Both gauges were attached to the same Langmuir condensation pump and the ionization gauge was separated from the McLeod gauge and mercury pump by a liquid air trap, which prevented mercury vapor and other condensible gases entering the ionization gauge. The entire system was evacuated and the metal parts of the ionization gauge thoroughly cleaned by bombardment as

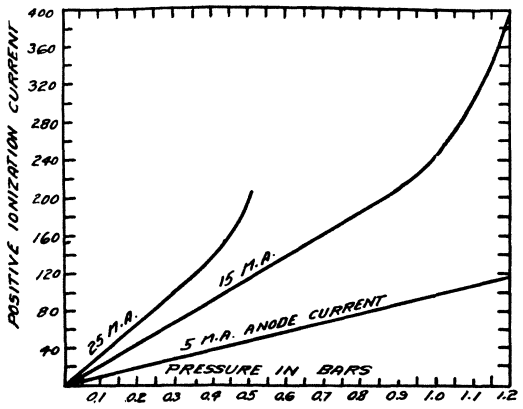

Fig. 4.

described above. Argon was then let into the apparatus and simultaneous readings taken on the McLeod and ionization gauges. The results of these observations are shown in the curves of Fig. 4. The three curves represent observations with three different electron currents. All show a straight line relation at the lower pressures and furthermore, this straight line when produced back passes through the origin. It, therefore, seemed justifiable to conclude that the ionization current under the above conditions, is directly proportional to the pressure for low pressures. As the pressure is increased the ionization current in-

creases more rapidly, due, no doubt, to ionization by collision. This conclusion is in accord with the observation that at the pressure at which the curve begins to increase, a faint blue glow may be observed in the gauge. It will also be noted that the lower the electron current, the higher the pressure at which the linear relationship fails to hold. In accordance with this observation it was found that 0.5 milliamps and 125 volts on the anode gave a linear relation up to 50 bars, as shown in Fig. 5, so that under these conditions the ionization gauge may be used

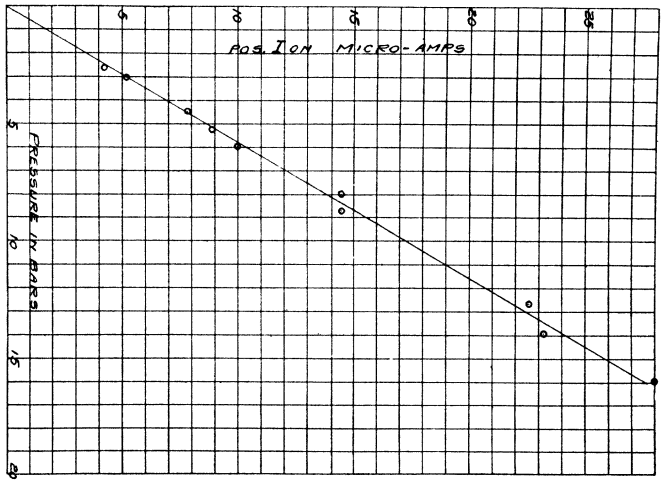

Fig. 5.

Argon.
Anode milliamps = 0.5.
Anode volts = 126.
Cylinder volts = − 22.
1 Bar = 1.72×10^{-6} amp.

to read fairly high pressures, while with 20 milliamps and 250 volts, the linear relation is only valid for pressures below about 1 bar.

Calibration of Gauge at Very Low Pressures.

In order to obtain a calibration of the gauge at pressures lower than those measurable on a McLeod gauge, a method was devised based on Knudsen's laws of flow.[1] A sketch of the apparatus is shown in Fig. 6. Two large bulbs A and B, are connected by a fine capillary tube, C; a McLeod gauge being connected to bulb A at M, and an ionization gauge G to bulb B.

[1] M. Knudsen, Ann. der Phys., *28*, 81 (1909). These relations are also discussed by S. Dushman, Gen. Elec. Rev., June, 1920, p. 493.

Both bulbs are directly connected at P_1 and P_2 through mercury traps S_1 and S_3 to a Langmuir condensation pump in series with an oil pump. Between bulb A and the capillary tube is another mercury trap S_2 followed by a liquid air trap L_1 which condenses the mercury vapor and prevents its flow through the capillary. The capillary is joined to

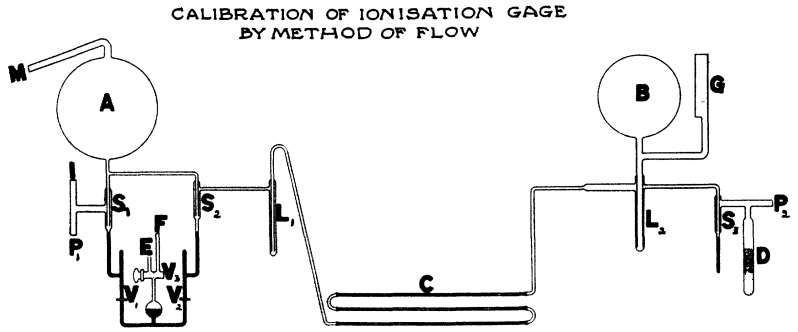

Fig. 6.

the bulb B, through a liquid air trap L_2, which serves to keep mercury vapor and other volatile gases out of the gauge. The complete system is evacuated to a high degree, special care being taken with bulb B, which is heated in an oven at 360° C. for an hour. After this treatment the ionization gauge is bombarded as described earlier in this paper, until the ionization current decreases to a very small value which does not increase when the gauge and bulb B are closed off by mercury traps S_2 and S_3 from the rest of the system. After the traps S_2 and S_3 are closed, bulb A is washed out with argon which is let in through I and when A contains from 10 to 20 bars of argon the trap S_1 is closed. When the trap S_2 between A and the capillary is opened the argon flows into the bulb B, and the ionization gauge. The rate of increase of pressure in B can be calculated from Knudsen's formula

$$Q = V\frac{dp}{dt} = \frac{P_A - P_B}{W\sqrt{\rho}}, \qquad (1)$$

where Q = quantity of gas flowing through the capillary per unit of time.

V = Volume of bulb B.

$\frac{dp}{dt}$ = rate of increase of pressure in B.

P_A = pressure in bulb A (read on McLeod gauge).

P_B = pressure in bulb B (ionization gauge).

W = "resistance" of capillary.

ρ = density of gas at unit pressure and temperature of capillary.

According to Knudsen,

$$W = \frac{2.394L}{D^3} + \frac{3.184}{D^2},$$

where L = length of capillary
D = diameter.

In the actual arrangement used for calibration, $L = 127.3$ cm., $D = 0.068$ cm.

Hence, $W = 9.68 \times 10^5 + 700$.

Furthermore

$$\rho = \frac{M}{83.15 \times 10^6 T} \text{ (gms./cm.}^3 \text{ at 1 bar)}$$

$$= 1.6 \times 10^{-9} \text{ gms./cm.}^3 \text{ at 1 bar for argon at 20° C.}$$

Also $V = 3100$ cm.^{3}

Since P_B was always very small compared to P_A, we can write equation (1) in the form

$$\frac{dp}{dt} = \frac{P_A}{V \cdot W \cdot \sqrt{\rho}}. \qquad (2)$$

The volume of the bulb A was so large, and the rate of flow of gas so

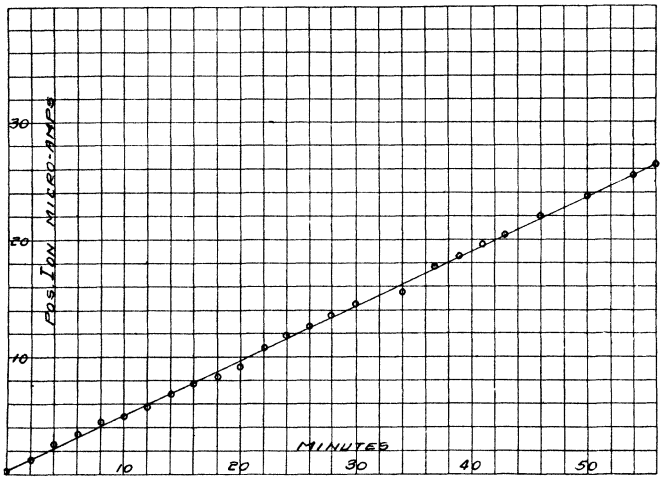

Fig. 7.

di/dt = .47 micro-amps. per min.
dp/dt = .006 bars per min.
$\therefore d/Li$ = .0128 bars per micro-amp.

Anode volts = 250.
Anode milli amps = 20.
Cylinder volts = − 22.
P_A = 12.6 bars.

small, that P_A remained practically constant during a calibration. Substituting in equation (2), the actual values for V, W and ρ, we obtain the relation:

$$\frac{1}{P_A} \cdot \frac{dp}{dt} = 4.98 \times 10^{-4} \text{ bars per minute per bar pressure in Bulb } A. \quad (2a)$$

Now let di/dt denote the observed rate of increase in the positive ionization current as read on the gauge G. Assuming a linear relationship between i and p, the value of di/dt ought to be a constant for any one set of observations. That this is true is shown by the results plotted in Fig. 7 for a set of measurements in which $P_A = 12.6$ bars. Similar results were obtained at different initial values of P_A, so that we can write

$$\frac{dp}{dt} = k \cdot \frac{di}{dt} \quad (3)$$

or

$$k = p/i. \quad (3a)$$

The following table gives a summary of the results of a series of such calibrations for argon at different values of $dp/(dt)$, as calculated from equation (2a) with an anode current of 20 milliamps and anodes potential of 250 volts.

$\left(\frac{dp}{dt}\right) = \left(\frac{\text{Bars}}{\text{Min.}}\right)$ Calc.	$\left(\frac{di}{dt}\right) = \left(\frac{\text{Amps} \times 10^{-6}}{\text{Min.}}\right)$ Obs.	$k = \left(\frac{\text{Bars}}{\text{Amps} \times 10^{-6}}\right)$.
0.0116	0.85	0.0145
.0112	0.91	0.0124
.0081	0.58	0.0140
.0071	0.52	0.0133
.0060	0.47	0.0128
.0059	0.44	0.0132
.0057	0.39	0.0146
.0056	0.52	0.0108
		Average 0.0132

That is, with an anode current of 20×10^{-3} amps. 1 microampere positive ionization corresponds to 0.0132 bar argon. With an ordinary galvanometer it is possible to read currents as low as 10^{-8} amps., corresponding to about 1×10^{-4} bar, and with more sensitive galvanometers much lower pressures can evidently be measured. Actually, the lower limit of pressures observed in the above measurements was about 0.005 bar. Since the linear relation holds down to this pressure, it seems quite justifiable to assume that it would be valid down to the lowest attainable pressures.

"INTERNAL CONTROL" CONNECTION.

With the electrical connections used in the above calibration, it was found, as has already been mentioned, that the positive ionization current is not quite proportional to the electron current. In view of the explanation given above, it suggested itself that the length of path traversed by the electrons would be practically independent of the current density, if the outer spiral is used as cathode, the cylinder as anode, and the inner spiral as collector. Under these conditions it was anticipated that the relation between positive ionization current and anode current would be linear. Fig. 8 shows that this is actually the case. From analogy with

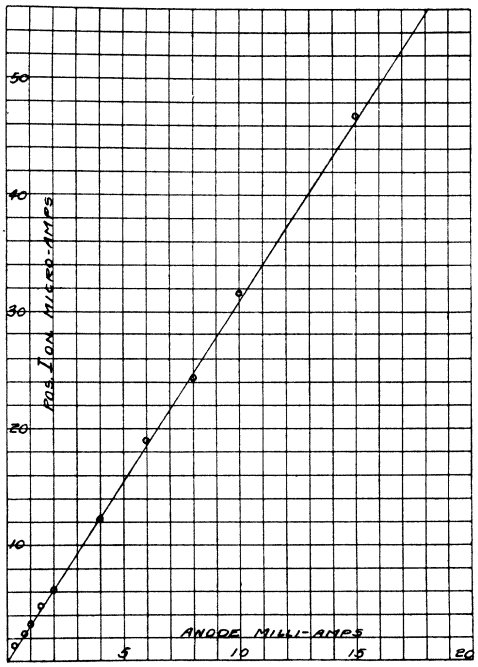

Fig. 8.

Argon at 1.85 bars.
"Internal control"
Cylinder volts = 250
Collector volts = − 22.

the similar type of connection used in wireless work we have designated this as "internal control" connection. Fig. 9 shows the relation between anode voltage and ionization current. This curve shows a rapid increase in ionization current up to about 80 volts, after which the curve is practically flat up to 250 volts (the highest voltage used). There is also

practically no change in ionization current for a variation in the potential of the inner spiral from 0 to 30 volts.

This method of connections has advantages over the first method, especially when it is to be used for measuring a considerable range of

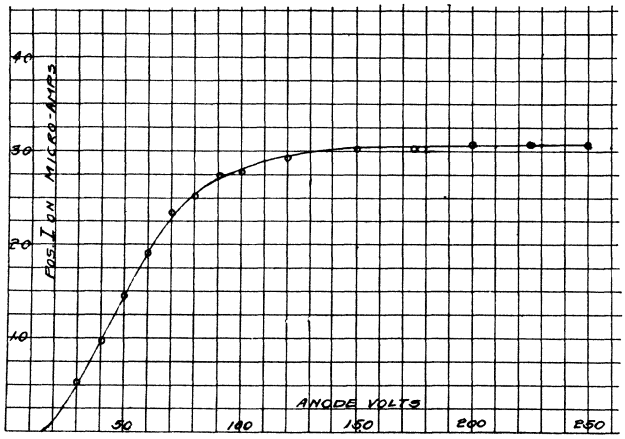

Fig. 9.

"Internal control"
Argon at 1.85 bars.
Anode milli-amps. = 10.
Collector volts = − 22.

pressures. The sensitivity of the gauge can be changed by merely altering the electron current and if we have a calibration for one value, we have it for all values, since it is a linear relation. Moreover, changing the anode voltage from 250 to 125 does not sensibly affect the calibration. On the other hand, with the first method of connection, we must actually calibrate the gauge for each electron current at which we desire to work. There is, however, considerable difference in sensitivity for the two connections. The constant, K, of equation (3)

$$k = p/i$$

when the anode voltage is 250, electron current is 20 milli-amps and collector voltage is − 22, is given below for the two methods of connections.

Cathode.	Anode.	Collector.	K
Inner spiral	Outer spiral	Cylinder	.013
Outer spiral	Cylinder	Inner spiral	.032

The sensitivity (as measured by microamps per bar) is evidently lower with the internal control connection. This is easily explained since with the first connection the electrons travel from the inner spiral almost to the cylinder and then back to the outer spiral, while in the second case they travel directly from the outer spiral to the cylinder. That is the sensitivity is in the ratio of the lengths of paths of the electrons. Thus, the second method has the advantage when a large range of pressures is to be measured, while the first method is more sensitive for measuring very low pressures, using the latter, pressures as low as 0.0001 bars have been measured. This corresponds to a positive ionization current of about 10^{-8} amperes which is about the limit for the ordinary galvanometer.

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