in the form of Eq. (4) show the linear form very well and from the value of C indicated by them one deduces an upper limit very close to the one Scott gives.

Attempts have been made to fit the data of this paper on Sargent[31] curves. For the light radioactive bodies it would seem that one can at best say that no striking regularity is thus exposed.

The data presented above are summarized in Table I.

The authors are very much indebted to Professor E. O. Lawrence and Professor J. R. Oppenheimer for many discussions of this work.

[31] B. W. Sargent, Proc. Roy. Soc. **A139**, 659 (1933).

TABLE I. *Summary of values for the upper limit of β-ray spectra from various elements.*

SUBSTANCE	TARGET	UPPER LIMITS INSPECTION	*K–U* LINES
$N^{13}+$	Acheson graphite soot	1.3 MV	1.5 MV
$F^{17}+$	O_2	2.1	2.4
Na^{24}	NaF	1.7	1.95
Si^{31}	quartz	1.8	2.05
P^{32}	red P	1.8	2.15
Cl	AgCl	4.8	1.5 6.1
A	A gas	2.7	1.5∽5
K	KF	3.5	1.4, 4.4

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The Ionization Gauge for Atomic Beam Measurements

R. D. HUNTOON AND A. ELLETT, *State University of Iowa*

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Use of two types of current measuring devices, galvanometer and vacuum tube amplifier, with an ionization gauge shows that the stable sensitivity,

$$\left(\frac{\text{positive ion current/mm gas pressure}}{\text{current fluctuation}}\right),$$

is greater for low electron emission densities thus favoring the use of the amplifier with its greater current sensitivity. Such factors as electrode size, relative potentials, electron emission, interelectrode leakage, type of inlet, gas adsorption, surface charges, temperature changes, B.K. oscillations, and variations of pumping speed which influence the design of a gauge are discussed and an arrangement to fulfill the necessary requirements is described. Performance tests show the gauge to be capable of measuring beam pressure changes at least as small as 3×10^{-11} mm of mercury or approximately 3×10^{9} mercury atoms per square centimeter per second.

THE properties of the ionization gauge method of measuring atomic beams are such that it would enjoy a wider field of application if the sensitivity were sufficient. Use by Zahl and Ellett[1] has shown no indication of the limitation attributed to adsorption phenomena by Johnson[2] but rather has indicated that the gauge might be capable of measuring beam pressure[3] changes of less than 10^{-10} mm of mercury. This, if true, would extend the range of usefulness to such a degree that a more careful investigation seemed advisable.

ANALYSIS OF MEANS OF EXTENDING SENSITIVITY

In normal use the sensitivity of an ionization gauge is determined by two factors, the magnitude of the electron current and the sensitivity of the positive ion current measuring instrument. Thus, to improve sensitivity, one may increase either the electron current or the sensi-

[1] Zahl and Ellett, Phys. Rev. **38**, 977 (1931).
[2] T. H. Johnson, Phys. Rev. **31**, 103 (1928).
[3] Unless otherwise indicated, all references to sensitivity are based on the effective pressure of the beam, expressed in millimeters of mercury, at the gauge inlet. Effective beam pressure is defined as that pressure inside a closed vessel which makes the number of molecules striking unit area of bounding surface in one second equal to the number transported by the beam across unit normal area in an equal time.

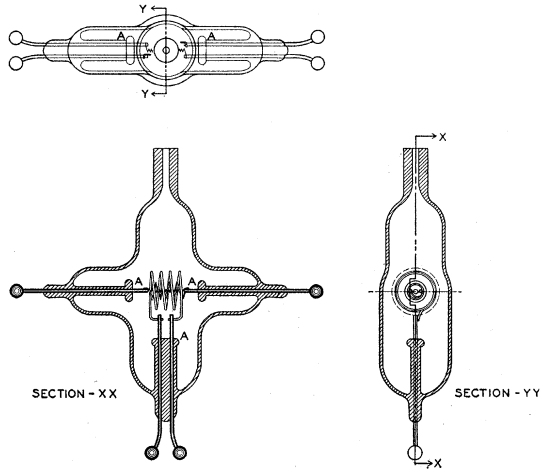

FIG. 1. Details of ionization gauge for beam measurements. Plate coil, 4 turns 8 mm dia. 0.015″ wire, length 7 mm; grid coil, 5 turns 3 mm dia. 0.010″ wire, length 7 mm; filament coil, 25 turns ½ mm dia. 0.005″ wire, length 7 mm.

tivity of the positive ion current meter until the critical ratio

$$\left(\frac{\text{positive ion current/mm gas pressure}}{\text{positive ion current fluctuation}}\right)$$

becomes too low. A fluctuation not exceeding ½ mm on the recording galvanometer, for an arbitrarily selected range, is considered satisfactory.

When measuring positive ion currents with a galvanometer having a constant of 4×10^{-11} amp./mm, the electron current can be increased to about fifteen milliamperes before fluctuations arising from sources other than the shot effect exceed the limit. The corresponding beam pressure sensitivity is of the order of 4×10^{-10} mm of mercury. The limiting factor seems to be instability in the thermionic emission.

The alternative, increased sensitivity of the positive ion current detector, remains. But this evidently is of no advantage unless the relative variations inherent in the first method can be reduced. Fortunately a decrease in filament temperature reduces the fluctuations in electron current more than the current itself; that is, the ratio $\Delta i/i$ becomes smaller. Hence, because of the linear relation between positive ion current and electron current, a decrease in electron current should permit a more than equivalent increase in the sensitivity of the positive ion meter with a corresponding net gain in performance. The beam sensitivity can be increased in this manner to a limit of approximately 2×10^{-11} mm of mercury at which point other difficulties become more important; but a recording device with a constant of the order of 10^{-13} amp./mm is necessary.

The design of a gauge to detect such small changes of pressure and to operate in conjunction with a high sensitivity current indicator requires consideration of the influences of various factors which will be taken up under the following heads: (1) shape and size of electrodes, (2) surface leakage (electrical), (3) potential of the electrodes, (4) instability in thermionic emission, (5) inlet resistance, (6) residual pressure in gauge, (7) Barkhausen-Kurtz oscillations, (8) effective ionizing path, (9) surface charges, (10) zero drift. In the following section each of the above factors will be discussed and the provision made for it in the gauge described. It is evident that the subjects are not mutually exclusive, but the division is a convenient one from an experimental standpoint. All references are to the gauge shown in Fig. 1.

GAUGE DESIGN

Electrodes

Fortunately, extensive investigation on the shape, size and position of the electrodes has been completed by Dushman and Found.[4] They find certain general forms to be better than others but the superiority lies more in stability and in linear response than in sensitivity. The general arrangement of electrodes they suggest has been maintained but certain revisions have been necessary for adaptation to beam measurements.

Gauges differing by a factor of two in electrode size and spacing showed little difference in sensitivity for low pressures and equal electron currents.

It will be noted that the collector electrode, as well as the other electrodes, is a tungsten spiral and that all electrodes have two leads sealed in. This permits outgassing of the individual elements by passing current directly

[4] Dushman and Found, Phys. Rev. **17**, 7 (1921).

through them. In this manner bursts of ionization resulting from the sudden release of gas in the usual bombardment heating are avoided. Use of a spiral collector electrode eliminates much of the evaporated oxide and metal arising from the outgassing of a cylinder and by reducing the surface decreases the amount of gas evolution during operation.

Sagging of the middle turns of the collector electrode during outgassing causes some difficulty if the coil is too closely wound. The inner turns get hot enough to sag before the outer ones are heated sufficiently. It was found that a spacing of 2 mm per turn with 0.015-in. wire was sufficient for coils up to 1.5 cm in diameter. End loss keeps the leads sufficiently cool to prevent any sagging of the element as a whole.

Surface leakage

It is necessary that the leakage across the gauge walls from all elements to the collector be kept small. Such leaks are usually very unsteady and would serve to mask entirely the small positive ion current changes. This means that the collector (plate) leakage resistance must be of the order of 10^{13} ohms. A sufficiently high resistance was introduced by sealing the collector leads through the envelope as far as possible from all other elements and by putting glass beads at points A (Fig. 1) to shield parts of the envelope from material driven off during the outgassing of the elements. The resistance in actual operation was 10^{15} ohms.

Potentials of electrodes

Although the potentials applied to the collector and grid are not critical, there are optimum values. The variation of positive ion current with collector potential is of the general form shown in Fig. 2, which would lead one to attempt operation at the maximum point. However, the critical ratio becomes too low before the maximum is reached and the instability is exceedingly great after the peak is passed (collector potential of about two volts).

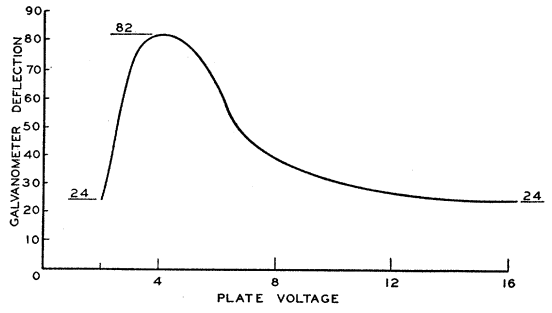

FIG. 2. Variation of positive ion current with plate voltage.

The increase in ion current can be attributed to change in space charge conditions and to lengthening of the effective ionizing path of the electrons. The smaller collector potential permits partial saturation of the positive ion current and also reduces the reverse potential gradient outside the grid. Both of these combine to allow the electrons to travel farther past the grid and produce more ions.

The increased instability could arise from electrons reaching the collector, the initiation of Barkhausen-Kurtz oscillations or the production of charges on the envelope.

If the above reasoning is correct, similar effects ought to be produced by an increase in grid potential, since it, too, would increase the length of path. It is found experimentally that grid potentials of more than 70 volts (collector, minus 20) introduce instability.

The conclusion is that one should use as high grid potential, or as small negative collector potential, as is consistent with stability and insulation.

Instability of thermionic emission

The reduction of instability ($\Delta i/i$) with temperature has already been mentioned. There remains the simple problem of choosing a filament with enough surface to give adequate emission at a low temperature with small power input. The resistance should also be high enough to make small contact variations negligible.

The filament shown, consisting of 25 turns of 5-mil tungsten wire formed into a 7-mm spiral by winding on a 15-mil wire as a form is sufficiently stable when operated by a storage battery with all connections carefully soldered. The emission should not exceed two milliamperes.

Inlet resistance

The gauge as normally used has a canal inlet which offers to the beam an impedance equal to that of a hole in a thin plate but resists the

escape of gas from the gauge with the full resistance of a tube. Experimental evidence[5] shows that the increase in sensitivity gained in this manner may be computed from Knudsen's laws of flow for gases at low pressure.[6] It must be remembered, however, that too great an increase in the resistance of the inlet will increase the recovery time of the gauge. If R is the Knudsen resistance of the canal and V is the gauge volume, the time constant of the gauge is RV. In practice V was from 6–10 cm^3 and R could be large enough to increase the sensitivity by a factor of ten to fifteen without causing RV to become unduly large (3–5 seconds).

Residual pressure in gauge

It is evident that the resistance of the inlet will maintain the residual pressure in the gauge at a value above that of the detector chamber and also increase the time to outgas the gauge for the preliminary clean-up. The effect of this resistance was determined by so arranging the set up that a ground glass plug with a bore 1.5 mm in diameter and 8 cm long could be removed at will. A beam was not used. As would be expected, the insertion of the plug caused an increase in pressure. The magnitude of the increase depended upon the previous treatment of the filament and outgassing of the gauge. The change accompanying insertion or removal of the plug decreased as the gauge was kept in operation and finally amounted to an alteration by a factor of about two.

Subsequent experience indicated that the use of a removable plug shortens the time of initial outgassing but does not reduce the final pressure enough to justify its use.

Barkhausen-Kurtz oscillations

Since the gauge is operated under conditions similar to those for producing B.K. oscillations, it is possible that the gauge might serve as a high frequency generator while in use. If so, it would be unstable because of its sensitivity to all changes of capacity in the vicinity.

The reactance introduced by the solenoidal electrodes should hinder the generation of these ultra-high frequencies. Also the observed stability accompanying operation at recommended potentials makes it seem unlikely that oscillations were present.

Effective ionizing path

Obviously any means which will serve to increase the electron path within the gauge should increase the number of positive ions per milliampere of electron current. It is not feasible, however, to achieve this with increased volume.

An attempt to increase the sensitivity by placing the gauge in a magnetic field showed but little effect, about 10 percent, for a field strength of 150 gauss. Increasing the field to 270 gauss decreased the effect to zero. The decrease in electron current because of increased space charge offset the gain in number of positive ions per milliampere.

One can also increase the path by using a smaller negative potential on the collector which allows the electrons to travel farther past the grid before being stopped. This has been discussed previously (electrodes).

Surface charges

It was thought that the open nature of the electrodes might introduce instability from surface charges, but none appeared which could be attributed to this source, while operating with recommended potentials.

Zero drift

A serious disadvantage of the ionization gauge is its lack of compensation for zero drift. The shift in zero point may arise from any of several sources, namely, changes in filament heating current, changes in work function of the filament, changes in thermal emissivity of the filament, changes in temperature of the bulb and surroundings, and changes in the residual pressure of the system.

Filament current changes can be reduced to such a point that they will have less effect than disturbances arising from other sources. A good storage battery and carefully soldered connections are essential.

Changes in work function and thermal emissivity can be corrected by maintaining the electron current at a constant value. This can be accomplished by altering the filament current

[5] Ellett and Zahl, Phys. Rev. **37**, 1112 (1931).
[6] M. Knudsen, Ann. d. Physik **28**, 75, 999 (1909).

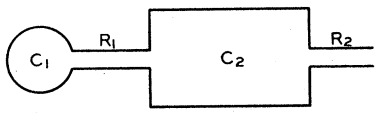

FIG. 3. Schematic diagram of detector chamber and pumping system.

either automatically or by manual adjustment, which is sufficient for most purposes.

Any shift in the temperature of the gauge will have a dual effect. It will change the equilibrium pressure built up by the canal inlet and will cause a change in electron emission. For convenience the gauge was mounted outside the system with only the canal inlet opening into the detector chamber. This arrangement should make temperature fluctuations larger than they would be with the gauge inside the vacuum system. Yet shielding from drafts removed all instability that could be attributed to this source.

Changes in residual pressure within the system are the most troublesome. Shifting of the level of liquid air in the traps is followed consistently by the gauge, as are fluctuations in pumping speed.

Theoretical consideration shows that reducing the fluctuations by means of a reservoir and connecting tubes of high resistance can only be accomplished with too great loss of pumping speed. Suppose, for example, a system of the type shown in Fig. 3 is used. C_1 is the detector chamber and R_2 is the combined resistance of the pump and connecting tube. We thus suppose R_2 to exhaust into zero pressure.

The differential equation for P_1, the pressure in C_1, is

$$C_2R_1C_1\frac{d^2P_1}{dt^2}+\left[C_2+C_1+\frac{R_1}{R_2}C_1\right]\frac{dP_1}{dt}+\frac{P_1}{R_2}-\left(1+\frac{R_1}{R_2}\right)Q_1-Q_2=0. \quad (1)$$

Q_1 and Q_2 are, respectively, the gas evolved from the walls of the chambers C_1 and C_2. Q_1 contains also the gas admitted by the beam. Solving (1) for the steady state gives the equilibrium value of P_1 which is

$$P_1=[R_1+R_2]Q_1+R_2Q_2. \quad (2)$$

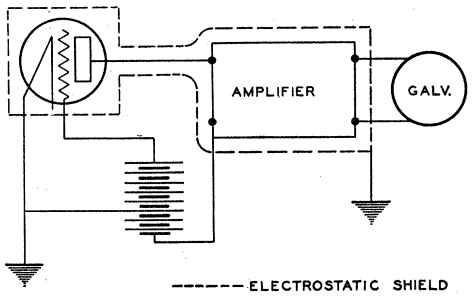

FIG. 4. Amplifier-gauge circuit.

Suppose R_2 abruptly changes to a value R_3, as would be the case if the pump speed changed. Using the value of P_1 from (2) as the initial pressure for the solution of (1) with R_2 replaced by R_3 and assuming $dP_1/dt|_{t=0}=0$ we find

$$P_1=-\frac{[R_3-R_2][Q_1+Q_2]}{m_1-m_2}[m_1e^{-m_2t}-m_2e^{-m_1t}]+P_{11},$$

where $m_1=[-A-(A^2-4B)^{\frac{1}{2}}]/2,$

$m_2=[-A+(A^2-4B)^{\frac{1}{2}}]/2$

and $A=(R_2C_1+R_2C_2+R_1C_1)/R_1R_2C_1C_2,$

$B=1/R_1R_2C_1C_2,$

$P_{11}=R_3[Q_1+Q_2]+R_1Q_1.$

Choosing the following values of the constants

$V_1=500$ cm^3 $\quad V_2=2000$ cm^3
$R_1=R_2=10^{-3}$ (a 1×10 cm tube approximately)
$R_3-R_2=10^{-5}$.

We find P_1 to have approximately the value

$$P_1=-10^{-5}[Q_1+Q_2][1.17e^{-.382t}-0.17e^{-2.6t}]+P_{11}.$$

Thus the time constant of the circuit is less than three seconds. The values of R_1 and R_2 are such that a pump speed of 20 liters per second will be reduced to about $\frac{1}{2}$ liter per second. The attainment of a 10-second response time would evidently seriously impair the pumping speed.

PERFORMANCE

The high sensitivity current measuring device used in connection with the gauge was a direct-current amplifier with a sensitivity of 1.56×10^{-14} amp./mm. It employed a type FP-54 vacuum

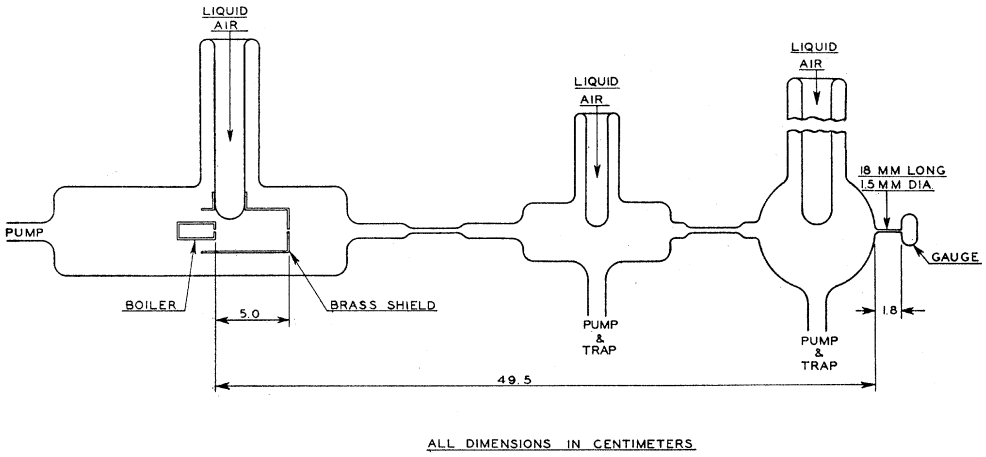

FIG. 5. Beam system for sensitivity measurements.

tube in a self-balancing circuit[7] and was connected to the gauge as shown in Fig. 4.

A beam system, as sketched in Fig. 5, served to make the necessary sensitivity measurements. Calculations on the basis of the boiler aperture, 0.016 inch diameter by 0.110 inch long, and the beam path, 49.5 cm, gives 1.68×10^{-7} as the ratio of beam pressure at gauge inlet to boiler pressure. The boiler aperture was treated as a hole in a thin plate, an approximation valid for all points on the axis of the aperture at distances large compared to its dimensions. The beam was interrupted when necessary by a magnetic shutter placed between the boiler and its liquid-air cooled shield.

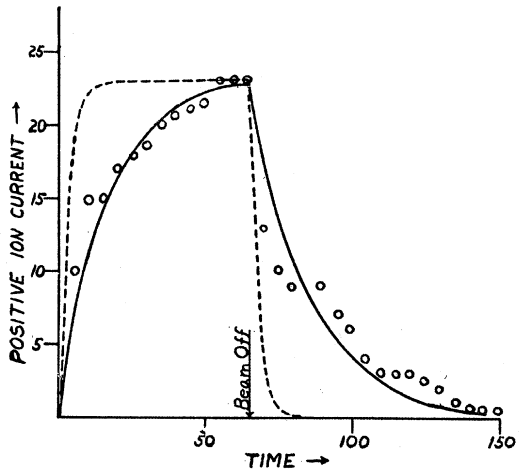

FIG. 6. Response to a beam of mercury. Circles, experimental points; solid curve, $y=23[1-e^{-t/15}]$ $0<t<65$ $y=23e^{-t/15}$ $65<t<150$; broken curve, $y=23[1-e^{-t/3}]$ $0<t<65$ $y=23\ e^{-t/3}$ $65<t<150$.

With a pressure of 0.0023 mm of mercury in the boiler corresponding to an observed boiler temperature of 28°C the gauge gave consistent readings of 18 mm with an instability of less than 1 mm and a relaxation time of about two minutes. This corresponds to a beam pressure sensitivity of 2.15×10^{-11} mm of mercury or its equivalent, 3.1×10^{9} atoms per second per square centimeter.

The experimental points in Fig. 6 show a typical response to a mercury beam. The dotted curve represents the theoretical response of a gauge with a time constant of 3 seconds, the computed value for the inlet used. It is evident that adsorption phenomena are playing a part in the response but that they do not influence the accuracy.

These results were obtained with the amplifier at one-tenth maximum sensitivity. An attempt was made to use the maximum amplification without success. Variations in pumping speed and the shifting of the level of liquid air in the traps introduced troublesome pressure fluctuations.

[7] Hart Brown and L. DuBridge, Rev. Sci. Inst. 4, 533 (1933).

Operating Notes

Baking procedure

Before being used, the gauge was baked at 350°C for 24 hours; the traps on the pumps were filled with carbon dioxide and baking continued for 3 hours at 380°C. If at any time the carbon dioxide traps were allowed to warm up, the process was repeated.

Preliminary cleaning of gauge

Safe flashing currents for the elements in the gauge shown are: 7 amperes in plate coil, 4 amperes in grid coil, and 2 amperes in filament.

The first flashing of the gauge elements after construction usually deposits a heavy film of tungsten oxide on the walls and causes a leak from grid to filament. This can be removed by treatment with aqua regia. Unless the source of potential supplying the grid is poorly regulated, the grid-filament leak should cause little difficulty and perhaps need not be removed.

Good vacuum conditions are important; all oxygen and water vapor must be removed before the initial flashing is started and none admitted during operation. Otherwise the filament will evaporate in addition to becoming poisoned.

Equilibrium

Several hours are required for equilibrium to be established after the traps are filled and the gauge lighted.

Optimum potentials

The equilibrium is sensitive to voltage changes and it is necessary to provide a constant source for each. The values found most suitable were $+67$ volts on the grid, -22 on the collector and sufficient filament current to give 2 milliamperes electron emission.

Magnitude of positive ion current

For mercury, positive ion current in amperes is of the order of $Pi/100$ where P is the pressure in millimeters and i is the electron current in milliamperes. This means that the change in plate current is about 1μ amp. for a change in beam intensity of 10^{10} atoms of mercury per second per square centimeter when using an inlet 1.5 mm in diameter and 2 cm long.

Note on the Use of Two Gauges

One naturally thinks of balancing two gauges in a bridge arrangement to neutralize zero drift and thus permit greater sensitivity. When using a galvanometer in the collector circuits such an arrangement is feasible. However, a little consideration shows it to be less sensitive than the single gauge and no more stable provided the single gauge is operated at an equal sensitivity and care is used in the construction of the vacuum system.

Balancing two gauges with amplification introduces difficulty. Two choices are available.

If one amplifier is to be used, either the whole unit with its supply batteries must be insulated from ground with a resistance greater than 10^{11} ohms or else the gauge and its batteries must be so insulated. In either event the whole arrangement would have to be shielded completely and thus become unwieldy.

If, on the other hand, one seeks to use two tubes in the amplifier, one is faced with the problem of balancing the circuit and at the same time compensating for the lack of symmetry in the two gauges by adjusting the sensitivity of each tube. Although this can be done, it seems too troublesome to lead to advantageous use of the gauge.

Conclusion

The ionization gauge can be used to measure beam pressure changes of the order of 10^{-11} mm of mercury or its equivalent, a change in beam intensity of 3×10^{9} atoms per square centimeter per second.

The use of two gauges to balance out unavoidable zero drift and thus permit greater sensitivity seems possible only at the expense of complicated or unwieldy apparatus.

There is little point in attempting to increase the sensitivity without improving the vacuum conditions or making provision for neutralizing residual pressure changes.