Sensitive Micro-balances and a New Method of Weighing Minute Quantities.

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In the course of experiments undertaken by the authors with a view to establishing a possible relation between the amount of ionisation produced at the surface of certain heated metals and the amount of oxidation of the metal, it became necessary to be able to measure changes of weight of the order of one-thousandth of a milligramme (1×10^{-6} gramme).

A micro-balance of the Nernst type was accordingly constructed which possessed the requisite sensitiveness, but considerable difficulty was experienced in obtaining consistent readings with it, owing chiefly to the inconstancy of zero and the great variation of sensibility with load. This latter defect is an inevitable consequence of the fact that a restoring couple due to gravity, the magnitude of which varies, as in the ordinary balance, with the position of the centre of gravity of the system relative to its point of suspension, is superposed on the restoring torque of the quartz fibre. Attempts to minimise this trouble led finally to the conclusion that for the purpose in view better results were to be expected from a gravity balance of the ordinary type in which the required degree of sensitiveness should be attained by making the beam very light. As the maximum load which it was intended to use on the balance was less than half a gramme, this could be done without loss of proportionate rigidity.

A beam, the weight of which was less than half a gramme, was accordingly made in the form of a plane frame-work of fused quartz rod of 0·6 mm. diameter. The ordinary knife-edges were at first replaced by pairs of very fine points ground on the ends of quartz rods; the central pair rested on a polished plane of quartz crystal; the ordinary pointer was replaced by a small concave glass mirror attached in line with the central axis.

With this beam it was found possible to weigh masses not exceeding one-fifth of a gramme with an accuracy of one-thousandth of a milligramme (1×10^{-6} gramme), and as it was clear that the sensitiveness of an instrument of this type could be still greatly increased, the possibility suggested itself of constructing an instrument sufficiently sensitive to detect and perhaps even to measure the changes of weight which radio-active substances are supposed to undergo. For, according to Rutherford,* the

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* 'Radio-active Transformations,' pp. 149 and 150.

amount of radium emanation given off by 1 gramme of radium bromide amounts approximately to 2×10^{-11} gramme per second, *i.e.* $1{\cdot}73 \times 10^{-9}$ gramme per milligramme per day. Assuming, then, that 10 milligrammes of radium bromide were available, the loss of weight per day would be approximately $1{\cdot}73 \times 10^{-8}$ gramme, and in order to detect this loss the balance would have to possess a sensibility of 1×10^{-8} gramme, and to be free from any wandering of zero which might mask or obliterate the real alteration of weight. After long continued experimentation and the introduction of numerous successive improvements in the details of construction an all-quartz constant-load vacuum gravity micro-balance has been designed and constructed in which the above conditions are completely fulfilled.

Two types of micro-balance have been constructed:—

Type A.—A micro-balance designed for the measurement of small alterations in weight of any substance and sensitive to one two-hundred and fifty-thousandth of a milligramme (4×10^{-9} gramme).

Type B.—A micro-balance for the absolute determinations in weight of masses not exceeding, in general, one decigramme, with an accuracy of one ten-thousandth of a milligramme (1×10^{-7} gramme).

Before proceeding to the description of the micro-balances a description of the balance-case and its attachments will be given. The same case has been used for both types of balance, and its construction will be made clear by reference to figs. 1, 2, and 3, which show respectively the front section, plan, and end section.

In order to ensure rapid equalisation of temperature the case was made as small as possible and of brass. The walls are about one-eighth inch thick and are carefully tinned both inside and outside to prevent the possibility of leakage due to the porosity of the brass. The case consists of the box-like base B and of the cover C and its inside dimensions are as follows:—Length, 12 cm.; height, 9·5 cm.; and width, 6 cm. The base and cover are each provided with a flange 1·5 cm. wide, and these two flanges are carefully ground together so as to make, when properly lubricated, a perfectly vacuum-tight joint. In order to separate the cover from the base without jolting the instrument, the flange on the base is provided with the lug *c*, that on the cover with a corresponding lug c_1, and the thumb-screw *d*.

A hole 5 × 4 cm. is cut in the end of the cover and over this is cemented a window of good plate glass. The whole case is supported by three brass legs D, on a marble base E, which is in turn supported by three levelling screws (not shown in the figure). The knife-edge of the beam rests on a plate of ground and polished quartz crystal, for the preparation of which we are indebted to our colleague Mr. H. J. Grayson. This plate *f* is cemented to the top of a brass pillar *b*, which is screwed into the solid block *g* in the base.

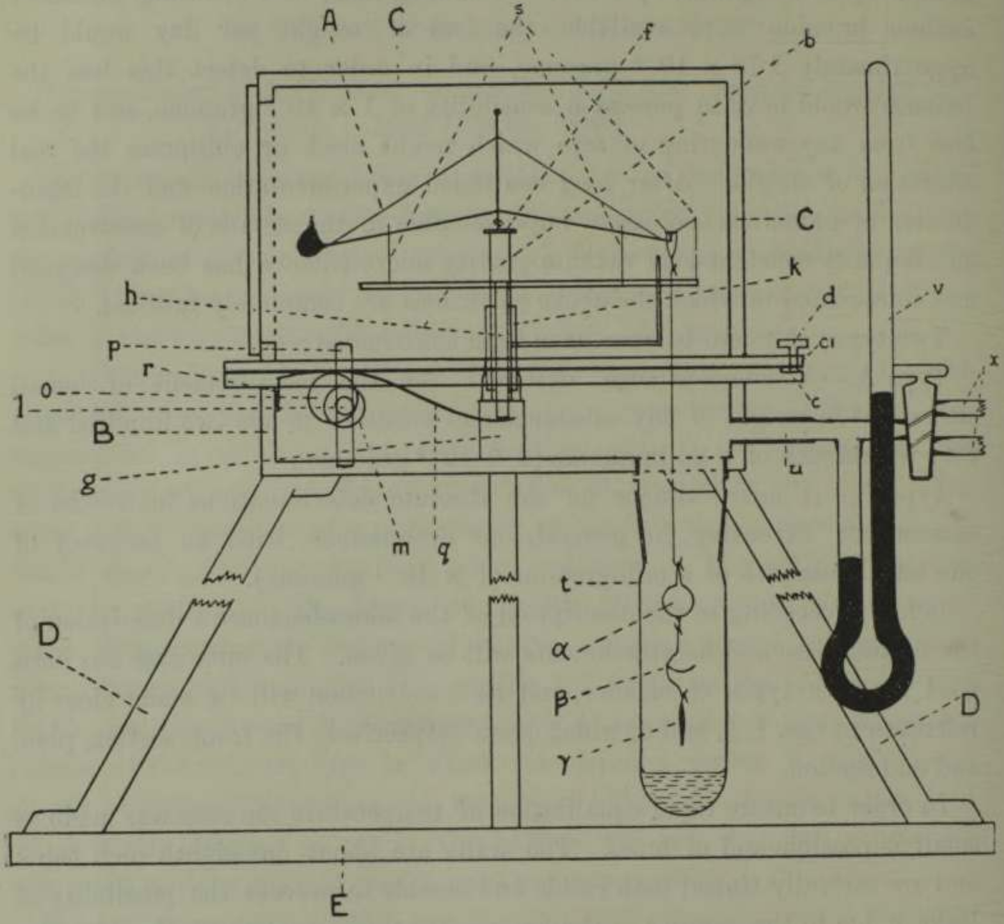

Fig. 1.

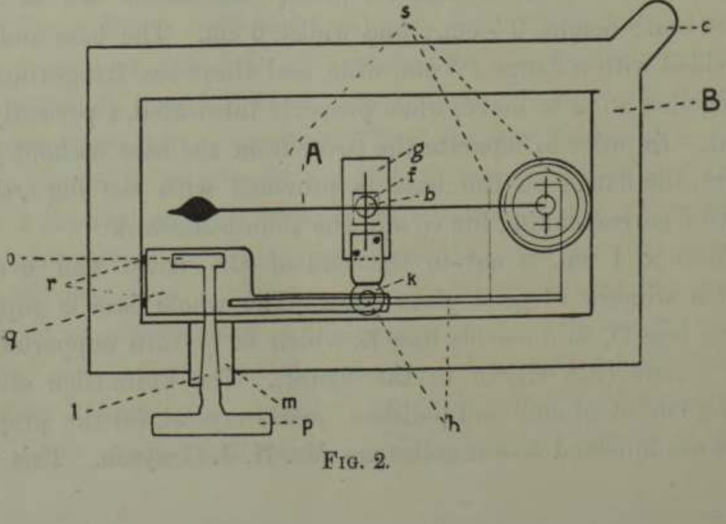

Fig. 2.

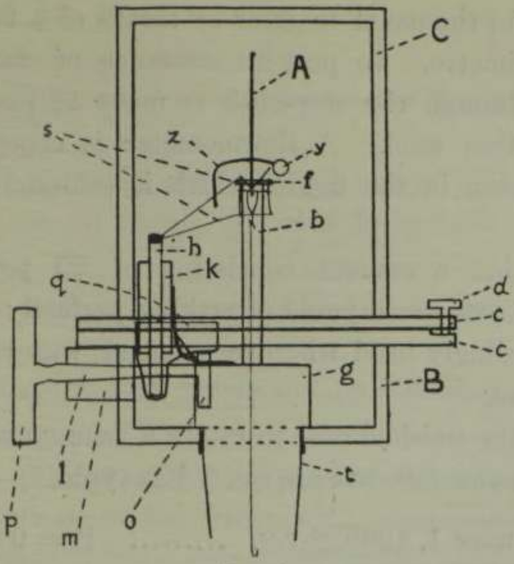

FIG. 3.

The attachments for the arrestment and release of the beam are as follows: The upright arm of a brass **T**-piece *h* passes through a hole along the axis of the rod *k*; an **L**-shaped piece of stout brass wire is attached to the rod *k*, and the vertical part of this passes through a hole in the horizontal part of the **T**-piece, which is thus free to move in a vertical direction only. The vertical movement is controlled by the excentric cam *o* on the end of the rotating piece *l*. The latter consists of a brass stopper carefully ground to fit the tapering tube *m*, and when properly lubricated makes a perfectly vacuum-tight joint and at the same time can be rotated freely. It is provided with a **T**-shaped vulcanite handle *p*, vulcanite being used to prevent as far as possible access of heat to the case when the handle is turned. The cam *o* works on a curved lever of brass *q*, which is hinged to the base at *r*, and by its rise or fall raises or lowers the **T**-piece *h*. The lever *q* is made broad at its hinged end so as to allow of the partial withdrawal of *l* for purposes of lubrication. To the **T**-piece *h* are cemented the **V**-shaped pieces of fine quartz rods which are adjusted so as to centre but not to raise the beam when the arrestment is lifted. The bottom of the base is provided towards one end with a hole 2·3 cm. in diameter into which is cemented the ground glass joint *t*. In the balance of type B the suspended parts hang into this tube, by removal of which access may be had to the scale-pan and counterpoise. A small quantity of calcium chloride in the bottom of the tube serves to dry the air within the case. The brass tube *u*, which is soldered to the case, has the manometer tube *v* cemented into it; connection with the atmosphere or with a Geryk vacuum pump is made through the two-way stop-cock *x*. The height of the mercury column in the manometer is read in the usual manner by means of a telescope and scale to a tenth of a millimetre. To prevent entrance of dust particles, the air entering the case through the stop-cock is made to pass through a tightly packed plug of cotton wool. A thermometer is cemented into a narrow brass tube (not shown in the figure) which is soldered into the top of the cover.

It was found that a cement consisting of 95 per cent. shellac and 5 per cent. oil of cloves was capable of making perfectly vacuum-tight joints, and this was accordingly used wherever cement was required in the construction of the case.

The capacity of the finished case to retain a vacuum was repeatedly tested and the following measurements are quoted as typical:—

February 1, 1909, 6 P.M. .... $P = 0{\cdot}41$ cm.
February 2, 1909, 10.5 A.M. ...... $P = 0{\cdot}41$ cm.

In order to damp accidental vibrations the levelling screws of the case are supported on glass plates lying on rubber corks 2 inches in diameter and 1 inch deep. This device was found sufficient to obviate all trouble of this kind.

The zero position of the instrument is determined by reading the position on a millimetre scale of the image of the filament of a Nernst lamp cast by the mirror attached to the beam. In the more sensitive balance of type A it was found that at pressures greater than about 2 cm. the heat from the source of light created considerable disturbances, and to minimise these the lamp was screened by a metal case with a small hole in it. The light passed through this hole and then through a flat glass cell containing a solution of alum to absorb as much heat as possible, and in addition a hollow double screen of asbestos was suspended in the path of the beam, which screen, by a pulley arrangement, could be raised for the moment when it was desired to read the position of the image.

We will now give a detailed description of each type of micro-balance.

Micro-balance A: A differential micro-balance capable of measuring alterations of not less than one two-hundred and fifty-thousandth of a milligramme (4×10^{-9} gramme).

The case having already been described, the description of the instrument and the method of calibrating and using it will now be given under the following heads:—

(*a*) The Beam; (*b*) Theory and method of calibrating and using the instrument.

(*a*) The beam consists of a framework of fused quartz rod of the form shown in figs. 1 and 2, A. Its dimensions along with its other constants are given in the table at the end of this section.

The use of fused quartz as the material of the beam has the following important advantages :—

(1) It is under all probable conditions of usage absolutely incorrodible, does not, as most, if not all metals, probably do, occlude gases, and is only slightly hygroscopic.

(2) It is very light, and in this respect has a further advantage over all metals except aluminium.

(3) Its tensile strength is very great, and its elasticity perfect within the limits of possible strain.

(4) Its coefficient of temperature expansion is exceedingly small, and consequently no distortion of the beam, with consequent alteration of the sensibility of the balance, is to be anticipated as the result of small temperature changes. This property also confers on the beam immunity from fracture during process of construction or subsequent exposure to high temperature.

(5) It is readily and cheaply obtainable in a condition of perfect purity and practical homogeneity. This latter condition, as will be shown below, is absolutely essential in a sensitive vacuum-balance.

(6) It is easily and safely manipulated with the oxy-gas flame, so that the beam can be quickly constructed, and the adjustments for balance, stability, and sensibility readily made in the manner described below.

(7) The whole beam consisting entirely of quartz, can be thoroughly and easily cleaned in a manner which would be impossible if any metal whatsoever entered into its construction.

The disadvantages of quartz as compared with metals lie in its small conductivity for heat and electricity. No trouble, to our knowledge, has arisen from the former of these causes; and the irregularities of behaviour, which were at an early stage of the experiments traced to the persistence of the electrification acquired by the beam during handling, have now been entirely obviated by ionising the air inside the case either by an X-ray discharge or, as is more convenient, by placing on the floor a small quantity of uranium oxide.

The form of the beam, that of a double triangle, figs. 1, 2, and 3, A, is one well adapted for ensuring rigidity. The slight inclination of the rods forming the lower sides of the triangle to the horizontal enables the centre of gravity of the whole to be brought close to the central knife-edge without the use of a subsidiary mass. The balance thus forms a single rigid system oscillating about a central knife-edge. Where the adoption of such a system is feasible, its advantages over the ordinary balance with its double suspended scale-pans are obviously very great.

The central and only knife-edge is ground upon the end of a quartz rod 0·6 mm. diameter and about 2 mm. long, which had been fused at the end to a blob 1 mm. in diameter. The length of the knife-edge is consequently about 1 mm.; the angle between its two planes is about 90°. These two planes are very carefully ground and the angle of their intersection, when viewed under a high-power microscope, showed as a perfectly straight line with no irregularities.*

In the earlier beams constructed, a double-point axis was used instead of a knife-edge, but this was found unsuitable for balances of high sensibility, as also was a modification of it formed by holding the two points for a moment in the oxy-gas flame in the hope that they would assume a perfectly spherical form. In this case they would give an equivalent ideal knife-edge passing through the centres of curvature of the spheres; but as a matter of experiment it was found that the departure from uniformity of curvature was too great to permit of constant sensibility over any finite range of oscillation. The double-sphere and double-point forms of knife-edge were consequently abandoned in favour of the above described knife-edge, which has been found to function in an entirely satisfactory manner.

In the earlier micro-balances constructed a very small concave glass mirror was attached by shellac to a projecting rod of quartz in line with the central axis. Small changes of zero which occurred were assigned with probability either to a steady evaporation of the shellac or to a viscous flow in it, producing a consequent shift in the position of the principal axis of the mirror. In order to avoid the use of a cement, some concave quartz mirrors (diameter 4 mm., focal length 25 cm.), with lug attached, were ground and polished. By means of the lug it was found possible to fuse the mirror directly to the beam. The position of the mirror relative to the knife-edge is shown in fig. 3, *y*.

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* The grinding of the knife-edges is easily done with the aid of a small holder in the form of a piece of hard steel 2 × 1 cm., across the centre of which is riveted a piece of brass 1 cm. square and about 2 mm. in thickness. Holes are drilled in the projecting end of the brass piece, and into these the quartz rods which are to be ground are cemented. The grinding is done on a piece of glass plate which has been ground with fine emery or carborundum, and the holder is moved on the plate in such a manner that it rests on the steel base and on the quartz rods. A gentle pressure is used in rubbing, and the holder is turned alternately so as to grind the ends to a chisel. The operation is finished off with very fine carborundum mud, and then a second piece of steel 2·5 × 1 cm. is secured on the back of the first piece so that it projects 2·5 mm. on either side of it. Resting the holder on this new edge, and again on the ends of the quartz rods, the latter are ground on a very finely ground glass plate without using any carborundum or emery, but with a little glycerine and water as lubricant. A gentle pressure is used in this final grinding. It is quite easy to make a set of three knife-edges in an hour or less.

Attached to the beam at its centre, and on the opposite side to the mirror, is a small piece of quartz rod with its end turned downwards at a right angle (fig. 3, *z*). This rod serves the dual purpose of balancing the mirror and of allowing the position of the centre of gravity of the beam to be adjusted. Attached to one end of the beam is a small quartz bulb of known internal volume, and containing air sealed up at known temperature and pressure. The object of this bulb will be shown immediately. At the other end is attached a quartz counterpoise of any desired shape, which will depend on the purpose for which the particular micro-balance has been constructed. The difficulties of adjustment for balance and for the position of the centre of gravity, which at first seemed insurmountable, disappeared with the discovery that quartz is appreciably volatile in the oxy-gas flame, and consequently, after a rough adjustment has been made by fusing on or removing small quantities of thin quartz rod to the counterpoise for balance, and either to the apex of the beam or to the subsidiary arm *z* for centre of gravity, the final adjustment is made with extreme ease by holding a projecting point on the counterpoise or on the apex of the rod *z* in the hot flame of the oxy-gas for periods of time varying from half a minute to a fraction of a second. Before making this final adjustment the beam is cleansed by boiling it for about 10 minutes in aqua regia and then for short intervals in successive quantities of distilled water. Unless the beam is thoroughly clean, no consistent readings are obtainable.

Finally, to accelerate any slow minute changes in the shape of the beam it is annealed for about 12 hours in a hot-air oven at about 200° C. Beams which have been treated in this manner show a quite remarkable constancy of behaviour, whereas, if the annealing be omitted, small and irregular changes of zero take place within a period of a few days.

Theory and Method of Calibration and Weighing.

A difficulty which faced the authors with the construction of the first micro-balance of a sensibility exceeding one ten-thousandth of a milligramme was that of constructing and calibrating a set of weights light enough to be used with it. The sensibility of the earlier balances was indeed determined by the use of a rider consisting of a measured length of quartz fibre, cut from a longer length which had been accurately measured and weighed on a delicate assay balance, but the practical difficulties of handling this rider convinced us that a set of such weights would be impracticable in actual size. This difficulty, which naturally increased with the attainment of a sensibility of the order of one hundred-thousandth of a milligramme, has been completely overcome by the adoption of what the authors believe to be an entirely new method of weighing, by means of which weights of the order of one-hundredth of a milligramme can be compared with the standard measures with an accuracy of one five-hundredth of their amount, *i.e.* the absolute value of such weights can be determined with certainty to one fifty-thousandth of a milligramme (2×10^{-8} gramme), while changes of weight can be measured of an order as low as one two-hundred and fifty-thousandth of a milligramme.

Not only is this new method of weighing remarkable for its accuracy, but also for its convenience and rapidity of working, in which respect it equals, if it does not surpass, the method of compensation, rider-adjustment, and oscillation employed with the ordinary precision balance.

The method depends for its successful application on the attainment of perfect homogeneity in the beam, this being the necessary and sufficient condition that the zero position shall be independent of the pressure of the air surrounding it. For if we have a balance of any perfectly homogeneous material, and the length of the arms—which may be considered of negligible weight compared with the loads—be l and l_1, if v and v_1 be the volumes of these loads, the density of the material being ρ, that of the medium in which the beam is immersed σ, then for equilibrium we have the relation $v(\rho-\sigma)l = v_1(\rho-\sigma)l_1$ or $vl = v_1 l_1$, that is to say, the equilibrium position is independent of the difference in density between the material of which the beam is composed and that of the medium in which it is immersed. Given such a beam, then, the method consists in employing as counterweight the whole or any fraction of the weight of the air contained in a sealed quartz bulb of accurately determined volume. The *rationale* of the method is as follows:—If a quartz bulb be filled with air at the same temperature and pressure as the air surrounding it, the effective weight of the contained air will, in accordance with the principle of Archimedes, be zero. If, however, the density of the air within the bulb differ from that of the surrounding air, then the inside air will possess a certain effective positive or negative weight. If v be the internal volume of the bulb which was sealed off at P_1 and T_1, then the weight of air within the bulb is $v\sigma_0 T_0/P_0 P_1/T_1$, if σ_0 is the density of air at normal temperature and pressure T_0 and P_0. If now the bulb be immersed in air at P_2 and T_2, its effective weight will be $v\sigma_0 T_0/P_0 (P_1/T_1 - P_2/T_2)$. If, again, the pressure and temperature of the air in which the bulb is immersed are changed to P_3 and T_3, the effective weight will be $v\sigma_0 T_0/P_0 (P_1/T_1 - P_3/T_3)$, and the change in effective weight will be $v\sigma_0 T_0/P_0 (P_2/T_2 - P_3/T_3)$; or, if the temperature be assumed constant, $v\sigma_0 T_0/P_0 (P_2 - P_3/T_3)$. If the balance is adjusted so that the zero position on the scale corresponds to P_2 and T_2, and a small amount of substance to be weighed be placed on the scale pan, the weight of this substance is given by the effective weight of the bulb. Thus in micro-balance A the internal volume of the quartz bulb, determined (as in all cases) by filling with mercury, is 0·0085 c.c. It was sealed at a temperature of 23° C. and a pressure of 759 mm. The weight of air contained in it is, therefore, 0·01012 milligramme, and by varying the pressure in the vacuum-case any value may be given to its virtual weight between this maximum value (which, of course, would only be exerted in a complete vacuum) and zero.

A change of pressure of 1 mm. in the case corresponds to a variation of the effective weight of $0·01012/759 = 0·00001333$ ($1·3 \times 10^{-5}$ milligramme), and an alteration of temperature of 1° C. at 20 mm. pressure to a variation of less than 1×10^{-6} milligramme. The temperature effect is therefore negligible at all pressures lower than 50 mm.* (the variation in volume of the quartz bulb with varying pressure in temperature is also negligible).

As the pressure in the case can easily be read to one-tenth of a millimetre, it is seen at once that an accuracy of determination of $1·33 \times 10^{-6}$ milligramme can be obtained provided the zero of the instrument remain constant and the beam be homogeneous.

As it is impossible to obtain quartz absolutely free from air-bubbles, the desired homogeneity in the beam was obtained by making all parts of rod drawn from the same sample of the best obtainable rod of large diameter. That the requisite degree of homogeneity is actually obtained in this way will be seen from the following results:—

Micro-balance, Type A, without attached bulb; sensibility (determined by placing a quartz rider on the beam and observing its position and the deflection produced) of such an order that a deflection of one scale-division corresponds to a change in weight of one one-hundred-thousandth of a milligramme (1×10^{-8} gramme).

Zero under observation from September 23, 1908, to October 8, 1908, during which period thirty-six (36) observations of the zero were made with the following results:—

24 readings of 608 and 12 readings of 607 scale-divisions were obtained. (No attempt was made to read closer than the nearest scale-division.) During this period the pressure was varied irregularly from 5 mm. to 8 cm.

At the conclusion of this series of observations the bulb was attached and sealed up and the beam again adjusted and calibrated.

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* The change in effective weight δw for an alteration of pressure δP_1 in the case is given by $\delta w = \frac{w \,.\, T \,.\, \delta P_1}{T_1 \,.\, P}$, or if T can be taken as equal to T_1 by $\delta w = \frac{w \delta P_1}{P}$, and for an alteration in the temperature of the case δT_1 by $\delta w = \frac{w P_1 \,.\, T \,.\, \delta T_1}{P T_1^2}$.

The constants of this balance are as follows:—

Total weight of beam with attached mirror, bulb, and counterpoise	0·177 gramme.
Length of arm	5·1 cm.
Volume of bulb..	0·00865 c.c.
Weight of air contained in bulb	$1{\cdot}02 \times 10^{-5}$ gramme.
Time of complete oscillation	35 seconds.

The extreme sensibility and accuracy of the balance is evidenced by the accompanying table, which gives the values of the pressure inside the balance-case and the corresponding scale-readings. The third column gives the calculated values of the scale-reading for each pressure on the assumption that the change in scale-reading is directly proportional to the change in pressure:—

Pressure (in mm. of mercury).	Observed reading to nearest mm.	Calculated reading.
4·3	631	(631)
4·5	632	632
5·6	638	636
5·7	637	636
6·4	639	638
6·6	640	639
7·0	642	642
9·8	650	650
12·2	658	658
15·2	668	668
15·7	670	670
17·4	674	676
22·5	694	693
28·7	715	(715)
35·8	738	736

The greatest difference between the observed and calculated scale-readings in this table amounts to two scale-divisions only, and this occurs in only four out of fifteen readings. The average discrepancy is considerably less than one scale-division. As shown above, the change in weight corresponding to a change of pressure of 1 mm. is $1{\cdot}3 \times 10^{-8}$ gramme, and since a change of pressure of 24·4 mm. produces a shift of 82 divisions in the scale-reading, the change of weight corresponding to one scale-division is equal to

$$\frac{1{\cdot}3 \times 24{\cdot}4}{83} = 3{\cdot}82 \times 10^{-9} \text{ gramme,}$$

i.e. less than one two-hundred and fifty-thousandth of a milligramme.

It follows that changes of weight exceeding this amount occurring in any substance attached to the arm of this balance can be observed and measured, even if the changes occur with considerable slowness, since we have shown that the resting point of the balance remains constant over long periods of time.

Description of micro-balance B. A micro-balance to determine in absolute measure weights not in general exceeding 1 decigramme with an accuracy of "at worst" one ten-thousandth of a milligramme (1×10^{-7} gramme).

This balance, like micro-balance A, is constructed wholly of quartz and consists of a beam almost identical in form and dimensions with that of A and one suspended system only. For the central axis it has been found advantageous to replace the small single knife-edge by a pair of knife-edges ground on the ends of two quartz rods about 1 cm. apart.

In place of the ordinary double scale-pan system a counterpoise is rigidly attached to one end of this beam, and the weight of the suspended system at the other end is always adjusted to equilibrate this.

Several different methods of attaching the suspended system to the beam have been tried. Of these, the ordinary knife-edge and plane of fused quartz have hitherto been found least satisfactory. A fine rounded point and plane have given good results up to a sensibility of about one four-thousandth of a milligramme, but proved unsatisfactory at higher sensibilities, while attachment by means of a short and very fine quartz fibre fused to the beam at one end and to a suspended hook at the other has proved much the best mode of suspension.*

Attached to the plane which rests on the end point (or to the fibre if such be used) is a hook which carries the suspended system.

This consists of a fine quartz rod with a hook at each end, a sealed-up quartz bulb α and quartz scale-pan β, both of which are similarly provided with two hooks, and a quartz counterpoise γ, which can be attached to the bottom of the scale-pan.

This type of gravity balance appears to us to offer some important advantages over the customary one. In the first place, the difficulties of construction are much diminished by the avoidance of the adjustments for

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* The attachment of the hook to the beam by means of the fibre is carried out as follows :—

A small T-piece of quartz is attached by one arm of the T to the end of the beam, the other end serving as a holder, to which a small rod of quartz can be fused for adjusting its position ; a hook is then put on one end of a piece of fine quartz rod ; holding now the beam in one hand and the hook in the other, the leg of the T-piece is fused to a globule in a very small oxy-gas flame, the straight end of the hook is now passed through the flame to touch this globule, and then the two are drawn apart about half a centimetre and at the same time withdrawn from the flame. A few trials will result in the production of a satisfactory flexible suspension.

placing the knife-edges in plane and parallel, and for equalising the length of arms.

In the micro-balance with fibre attachment the want of perfect flexibility of the fibre conditions an alteration in the length of arm for different positions of the beam, but, since the counterpoise and substance to be weighed are both attached to the same hook on the fibre, this cannot introduce any error into the weighings, which are in such a case independent of the length of arm.

The method of weighing with this balance is as follows:—

(*a*) The quantity of substance to be weighed does not exceed the total weight of air contained in the bulb. In this case the pressure inside the balance-case and the resting point having been taken with the scale-pan empty, the substance to be weighed is placed on the pan and the pressure adjusted until the same resting point is obtained. If w is the total weight of air contained in the bulb, which was filled at the pressure P, and P′ represents the difference in pressure required to recover the original resting point, then the weight of the substance is $w\text{P}'/\text{P}$.

(*b*) The quantity of substance to be weighed exceeds the weight of air contained in the bulb.

In this case it is necessary to prepare one or more counterpoises which must be lighter than the original one, and must differ from each other by a known amount not exceeding w. It is obvious that such counterpoises can be easily made, and their difference in weight determined with great accuracy by the above described method on the micro-balance itself.

With a series of such counterpoises, which take the place of a set of weights, quantities of any substance not exceeding in weight that of the heaviest counterpoise can be weighed with an absolute accuracy equal to that with which the weight of air in the bulb can be ascertained, and with a relative accuracy depending on the capacity of the instrument for recovering its zero, and on the accuracy with which the pressure can be read.

It has been found preferable to take the actual resting point of the balance rather than to determine this from its oscillations. The oscillations of both types of micro-balance have been found to damp rapidly, five to ten minutes being sufficient for the instruments to come to rest. The damping factor is nearly but not quite independent of the pressure, and is greater for the point and plane suspension than for the rigid system, or for the beam with quartz fibre suspended system.

Behaviour of Micro-balance, Type B.

Figures will be quoted showing the behaviour of this balance both with point and plane suspension and with fibre suspension.

Total weight of beam and suspended system	0·93 gramme
Volume of bulb	0·422 c.c.
Amount of air contained in bulb	$5{\cdot}04 \times 10^{-4}$ gramme.
With point and plane attachment, time of swing	13·5 seconds.

The following are typical successive readings of pressure and resting point:—

P = 72·2 mm. Resting point = 620.

Four readings after arresting the beam each time gave the same resting point.

The scale-pan and counterpoise were removed, after which

P = 72·0 mm. Resting point = 620.

The zero is therefore not disturbed by manipulations necessary in weighing.

This has been repeatedly shown. The sensibility was such that a change of pressure of 3·3 mm. caused a change in the resting point of nine scale-divisions, therefore, since a change in pressure of 1 mm. represents a change in effective weight of $\frac{5{\cdot}04 \times 10^{-4}}{760}$.

A change of resting point of one scale-division represents a change in weight of $\frac{5{\cdot}04 \times 10^{-4} \times 3{\cdot}3}{760 \times 9} = 2{\cdot}43 \times 10^{-7}$, that is, less than one four-thousandth of a milligramme.

The volatility of quartz in the oxy-gas flame can be well shown by an instrument of this sensibility. Thus before placing the counterpoise in the flame the readings were

P = 72·0 mm. Resting point = 620.

After placing in the flame for less than one second,

P = 64·7 mm. Resting point = 620.

Difference in pressure = 7·3.

Loss in weight = $\frac{5{\cdot}04 \times 10^{-4} \times 7{\cdot}3}{760} = 4{\cdot}83 \times 10^{-6}$ gramme.

The loss in weight is relatively very considerable if the time of heating is slightly increased; thus in a second experiment before heating the counterpoise

P = 64·7 mm. Resting point = 620.

After heating for two seconds,

$$P = 41{\cdot}3 \text{ mm.} \qquad \text{Resting point} = 620.$$

Therefore loss in weight $= \dfrac{5{\cdot}04 \times 10^{-4} \times 23{\cdot}4}{760} = 15{\cdot}52 \times 10^{-6}$ gramme.

The behaviour of the same balance with fibre suspension is shown by the following typical figures :—

Time of swing	33·0 seconds.
Pressure	13·5 mm.
Resting point in five successive readings after arrestment each time	559 or 560
Pressure	6·0 mm.
Resting point in five readings after arrestment each time	688

A change in pressure of 7·5 mm. causes a change in resting point of 128 scale-divisions, and the sensibililty is therefore $\dfrac{5{\cdot}04 \times 10^{-4} \times 7{\cdot}5}{760 \times 128} = 3{\cdot}88 \times 10^{-8}$, or less than one twenty-five thousandth of a milligramme.

That no appreciable change in weight is caused by the careful handling of the quartz scale-pan and counterpoise is shown by the recovery of the resting point after these had been removed and replaced, when

$$P = 6{\cdot}1 \text{ mm.} \qquad \text{Resting point} = 689.$$

Calculated resting point for this pressure = 690.

Of the micro-balances described in the foregoing pages, micro-balance A was designed some months ago with the object of measuring the loss in weight which radium salts are supposed to undergo during disintegration.

If the generally accepted views as to the nature and magnitude of these changes are correct, the instrument is amply sensitive for the purpose; if greater sensitiveness is desirable it can easily be obtained by still further lightening the beam, or lengthening the time of swing. We had hoped to have been able to crucially test this question, but all our efforts to obtain a few milligrammes of radium bromide have been unsuccessful. Although we have not yet given up hope of obtaining what we require, we have thought it better to publish a description of this balance as well as that of the less sensitive instrument which we have called Type B, as it seemed to us that many problems might present themselves to other investigators the solution of which might be materially assisted if such an instrument were available.