Sept. 13, 1932. G. ISING 1,877,243

GALVANOMETER

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Fig. 1.

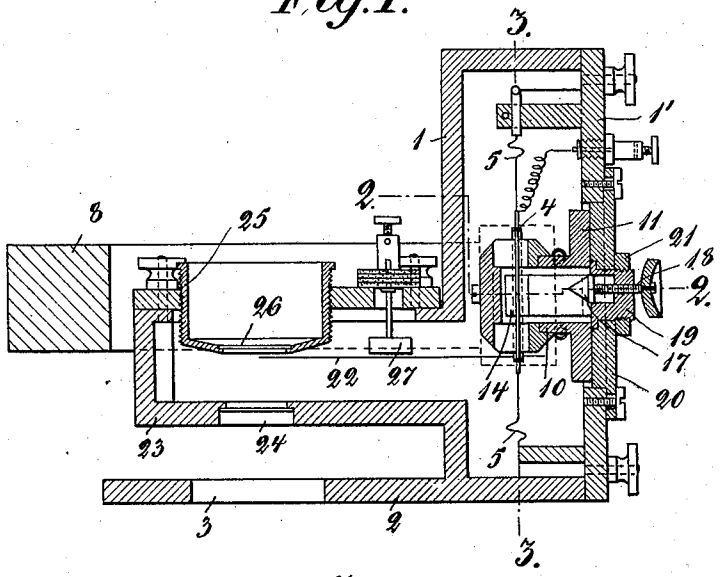
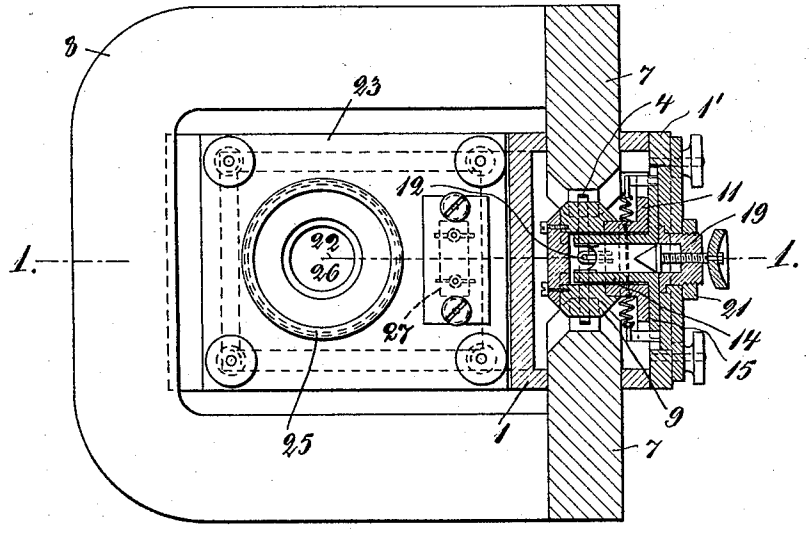


Fig. 2.



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Fig. 3.

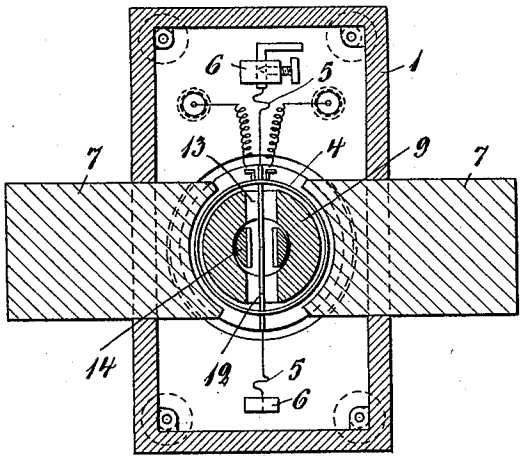


Fig. 4.

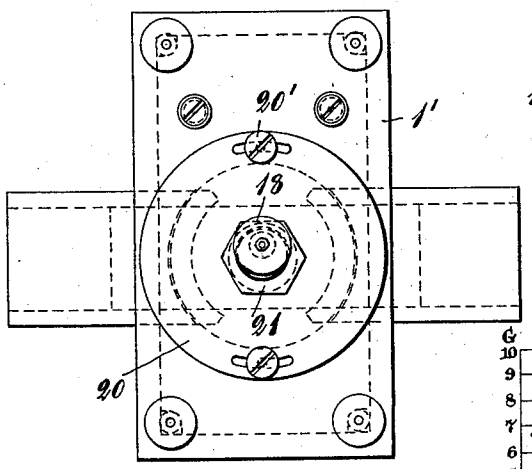


Fig. 5.

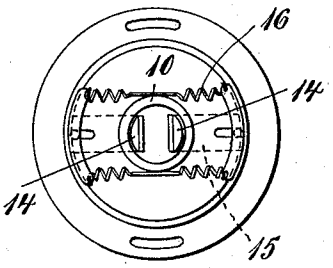


Fig. 7.

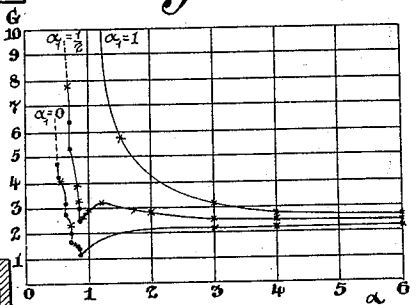
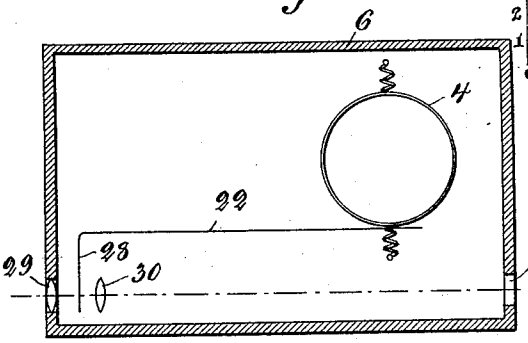


Fig. 6.



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GALVANOMETER

Application filed October 16, 1929, Serial No. 399,991, and in Sweden October 19, 1928.

The present invention relates to moving-coil galvanometers, and has for its object to increase the sensitivity of such instruments to substantially the highest degree obtainable from a theoretical point of view, even to a microscopic degree requiring microscope instrumentalities. The discoveries upon which the invention is based have shown that certain essential conditions must be complied with in designing an instrument having a sensitivity of such high degree, and the invention resides in a combination of means by which the said conditions are all simultaneously complied with.

As is well known, there has existed a certain definite limit above which the sensitivity of a galvanometer could not be increased. Said limit was determined by the occurrence of such irregular oscillations of the movable system about its position of equilibrium as are caused either by shocks of the molecules of the surrounding medium or by small irregular current fluctuations of molecular origin in the closed circuit. From the "equipartition principle," it follows that the mean amplitude of the resulting Brownian movement of the coil will be the same, whatever be the cause of this motion.

According to the invention, the maximum theoretical limit of the sensitivity of a galvanometer is in effect reached, on the one hand, by increasing the optical accuracy to such extent as to make the said Brownian fluctuations visible; and on the other hand, by choosing a theoretically favorable value of the damping of the movable system; and by removing the influence of external disturbances and concussions. The ideal conditions contemplated by the present invention are as follows:

(*a*) The magnification of the deflection produced by optical means should be so high, that the mean value of the Brownian fluctuations corresponds to a small fraction, for instance 1/15–1/10, of a division on the reading-off scale, which scale is itself just discernible by the naked eye.

(*b*) In order to reduce the apparent current fluctuations, which correspond to the Brownian vibrations of the coil, as nearly as possible at fixed values of the time required for the deflection and at fixed values of the resistance of the coil circuit, the electromagnetical damping should not be made too small. If the so-called critical damping (which corresponds to the aperiodical limit) is chosen as unit, the said electro-magnetical damping should not be appreciably smaller than unity and should preferably considerably exceed the air damping.

(*c*) The instrument should be free from external disturbances to such extent that the temporary displacements of the zero position, caused by such external influences are, on an average, smaller than the mean value of the Brownian fluctuations.

In order to embody the condition (*a*), the coil is in one form provided with a light pointer, consisting, e. g., of a fine quartz or glass wire, the end of which is observed under a very high microscopic magnification. In order to make it possible to use an observation microscope with high numerical aperture, the instrument is so devised that a powerful observation objective may be placed close to the end of the pointer. At very high microscopic magnification, the image of the pointer may be rather blurred, even with high numerical aperture. In order to increase the accuracy of the reading still further, means are provided by which it is made possible to make clearly visible the diffraction fringes accompanying the image of the pointer and to read off the deviation of the pointer by observing the displacement of these fringes on a scale.

The condition (*b*) may be deduced from the following reasoning:

If ϕ is the deflection of the coil system, and A the elastic control (i. e. the restoring moment for unit angular displacement) the mean value $\bar{\phi}$ of the amplitude of the irregular Brownian deflections, according to the equipartition principle, is determined by the expression

$$(1) \quad 1/2A\bar{\phi}^2 = \xi$$

in which ξ is the molecular energy per degree of freedom of the system, said energy at room

temperature being equal to 2.10^{-14} ergs. If the Formula (1) is combined with the general equations of movement for a galvanometer system, the mean value of the apparent current variation, $\bar{i}$, corresponding to the value of $\bar{\phi}$ determined by (1), will be found to be

$$(2) \quad \bar{i} = \sqrt{\frac{2\pi\xi}{R \cdot t}} \cdot G,$$

in which expression R is the total resistance of the galvanometer circuit, G is a quantity dependent on the damping of the movable system, and t is the time of indication, i. e. the time elapsing from the closing of the circuit until the movable system, within a certain tolerance (in the present case, 1/1000 of the final deflection), has reached its end position. If α and α_1 are the values of the total damping and the air damping respectively, measured in the critical damping as unit, the factor G in (2) may be written

$$G = \frac{f|\alpha|}{\alpha - \alpha_1}$$

in which the function $f(\alpha)$ gives the ratio t/T between the time of indication t and the period of oscillation T (in undamped condition).

As may be seen from (2), the obtainable current sensitivity, which is obviously inversely proportional to $\bar{i}$, is proportional to $\sqrt{Rt}$. On the other hand, the factor G is also of considerable importance for the result, and should be made as small as possible. The curves in the accompanying diagram illustrate the relation between the factor G and the value of α at three different values of α_1. As may be seen from the curves, the smallest value of G for small values of α_1 corresponds to a value of α slightly less than unity, while, for any value of α_1, a somewhat higher but still small value of G may be obtained by making α great and considerably greater than α_1. This is obviously just the condition (b) which should be satisfied at least when the external resistance of the coil circuit is small, i. e. when the instrument is short-circuited. As will be seen, the condition $\alpha_1 < \alpha$ which is included in (b) stands in a certain contradiction to the condition (a), as the limitation of the air damping will obviously limit the pointer length, while, on the other hand, a great pointer length is of course favorable for reading small deflections. It will accordingly be necessary to compromise between the conditions (a) and (b) in regard to the pointer length. It will be explained below in what way this may be done to the best advantage.

The condition (c), according to which the instrument should be substantially free from external disturbances, is complied with by making the coil exactly symmetrical with respect to the rotary axis and suspending it between two short torsional wires, which are tightly stretched.

In practice the galvanometer is designed with such small dimensions, and in such a shape, that it can be placed on the stage of an ordinary microscope, the ordinary condenser of the microscope being then preferably replaced by a weak microscope objective. Designing the instrument in said manner has the advantage that the optical equipment and the adjustment devices of an existing microscope may be used in connection with the use of the galvanometer.

A further suitable arrangement which is useful, particularly in connection with very delicate coils, consists in providing the coil with a connecting piece in the form of a thin rod extending in the direction of the axis of symmetry (rotary axis), which rod connects two diametrically opposite points of the coil and serves as a stiffening "spine" of the coil. This spine facilitates an exact attachment of the suspension wires (torsional wires). It takes up the tensile stress of these wires so that said stress does not deform the delicate windings of the coil. Furthermore, the said spine is adapted to be engaged by the damping means of the instrument when the coil is to be arrested.

The invention will be more closely described with reference to the accompanying drawings. Figure 1 is a vertical section on the line 1—1 in Figure 2 of a moving coil galvanometer designed according to the invention and adapted to be mounted on the stage of an ordinary microscope. Figure 2 shows the same instrument partially in plan view and partially in section on the line 2—2 in Figure 1. Figure 3 is a vertical section on the line 3—3 in Figure 1. Figure 4 is a side elevation of the instrument as viewed from the right hand side in Figure 1 or 2. Figure 5 is a detail of Figure 2. Figure 6 is a diagrammatic section of another embodiment of a moving coil galvanometer according to the invention on a plane parallel with the coil and the pointer. Fig. 7 is a diagram illustrating the performance characteristic of the invention.

In the embodiment according to Figures 1 to 5 the moving coil system is disposed in a rectangular casing 1 the bottom side of which extends into the bearing plate 2 adapted to rest on the stage in an ordinary microscope and provided with a circular aperture 3 the centre of which co-incides with the axis of the microscope at the correct positioning of the instrument on the microscope stage.

The moving system of the instrument consists of a circular coil 4 suspended between two fine torsional wires, stretched by means of springs 5 fixed at projections 6. The coil can turn in usual manner between the pole faces 7 of a permanent horse shoe magnet 8 enclosing the rest of the instrument which

pole faces project inwards through opposite sides of the casing. The coil 4 surrounds an annular core 9 of soft iron supported by a collar 10 which projects into the casing from a plate 11 disposed inside the supporting plate 1′ forming a side wall of the casing. In order to prevent deformations of the light coil and to facilitate the arresting, two opposite points of the coil co-inciding with the axis of rotation are united by means of a stiffening connection 12, consisting of a rod or tube, for which axial bores 13 are disposed in the annular iron core 9.

In the inner cavity of the annular iron core 9 an arresting device for the coil is disposed and adapted to engage the rod 12. Said arresting device consists of two holding clamps 14, preferably provided with a coating of cork or the like and adapted to approach or to move away from the rod 12 symmetrically. The holding clamps consist of angular pieces the feet 15 of which are slideably disposed in horizontal slots in the plate 11, and are, by means of helical springs 16 (Fig. 5), brought to bear against a conical member 17 disposed on the arresting screw 18. Said screw extends somewhat eccentrically through a bushing 19 which is rotatably journalled in a disk 20 secured to plate 1′. The outer end of the bushing 19 is provided with a threading carrying a stop nut 21.

On the drawings the clamps are shown in separated position. At the arresting the conical member 17 is moved outward by turning the screw 18 the clamps then being pulled together and squeezing the rod 12.

On account of the delicacy of the movable system it is necessary that the holding clamps engage the rod parallelly and simultaneously. To adjust the clamps to be parallel with the rod 12 the circular plate 20 is adapted to turn a small angle after the screws 20′ (Fig. 4) have been loosened.

The symmetrical adjustment of the holding clamps to equal distances from the rod 12 takes place by turning the bushing 19 after loosening the stop nut 21. After the adjustment of the arresting device has been carried out in this manner the coil may safely be engaged by said device without a previous slackening of the suspension string.

The coil 4 carries at its lower portion a pointer 22 consisting e. g. of a fine quartz or glass wire. Said pointer projects into a flat box or pocket 23 extending from the casing 1. In the bottom side of the pocket a glass window 24 is disposed to illuminate the pointer. The upper side of the box 23 consists of a detachable lid into which a cap 25 turned upside down is tapped which cap at its bottom is provided with a thin glass window 26 disposed closely above the end of the pointer opposite the window 24. The cap 25 is intended to accommodate the observation objective. By this disposition the observation objective may approach the pointer while the interior of the galvanometer remains closed so that no disturbing air currents may penetrate thereto.

The same end can alternatively also be attained without the concave cap 26, in case the microscope objective is introduced into the interior of the instrument through an aperture in the top of the box, the objective being then enclosed by a soft packing, by way of example a rubber packing, at the point of introduction.

The lid of the projecting flat box 23 carries in the shown embodiment of the galvanometer also two insulated small metal plates 27, (Fig. 1) which normally are not in use and are then coupled to the instrument casing but which in certain researches may serve to reduce the directional force of the movable system by means of electrostatic charging i. e. to astatize the instrument. The indicator 22 should then be electrically conducting.

Although the above described arrangement of an instrument which can be mounted in an ordinary microscope brings certain important advantages it may be suitable in order to obtain the utmost permanency of the zero point, to mount the microscope objective on the galvanometer proper as is diagrammatically shown in Figure 6. In contradistinction to the above described embodiment in which the optic axis is parallel with the axis of rotation of the coil system the optic axis is according to the embodiment in Figure 6 perpendicular to the axis of rotation and parallel with the pointer 22. The latter is provided with an extension 28 bent at a right angle which projects downward between an observation objective 29 disposed in a light aperture in the instrument casing 1 and an illumination objective 30 also disposed close to the pointer. The light from a source of light 31 disposed outside the instrument casing enters through a light aperture 32 into the casing, which aperture is disposed right opposite the light aperture of the observation objective. The arrangement according to Figure 6 brings the advantage that variations in the temperature and therefrom resulting thermic expansions only have the smallest possible influence upon the position of the objective or the objectives in relation to the pointer, in such a way that even at a very high magnification the zero position of the galvanometer and the accuracy of the image are substantially variable.

Said arrangement has furthermore the advantage that a central diaphragm may be constructively embodied with the observation objective in such a manner that said diaphragm may be disposed on or removed from the objective from the outside without open-

ing the instrument. Such an easily shiftable arrangement of a central diaphragm in an instrument of the present kind brings certain advantages as will be described in the following. In the case of a high microscopic magnification the reading-off of the deflection is preferably carried out by means of the diffraction fringes accompanying the blurred image of the indicator. At a given value of the microscopic magnification the width of the fringes are smallest i. e. the accuracy in the reading-off highest, if only certain edge portions of the objective cooperate to produce the image. This is attained by using a central diaphragm. Especially in the photographic registration of small deflections said central diaphragm is of importance to obtain the utmost sharpness of the fringes. The diffraction fringes obtainable without central diaphragm are not quite so sharp but adequate for subjective reading-off. They may also, on account of their higher brilliancy, be of advantage in photographic registration in case the highest attainable distinctness is not required.

The dimensioning of the movable system inclusive of the pointer will be of special importance if the object in view is to obtain the highest possible degree of sensitivity in the galvanometer. It is previously known (see Phil. Mag. vol. I, April 1926, page 827) that there is a certain limit for the sensitivity, depending upon the erratic Brownian fluctuations in the position of the galvanometer system. In order to be able to reach said limit without evacuating the instrument, which would involve great difficulties both for the manufacture and the operation of the instrument, one must follow certain rules stated below in dimensioning the instrument. The damping by air friction acting upon the movable system should be less than the electromagnetic damping at closed circuit, and should preferably only deliver a smaller portion of the critical damping i. e. the damping required to render the motion of the system only just aperiodic.

To dimension the movable system of the galvanometer in such a manner that said limit of sensitivity is reached the following dimensioning rules have to be followed.

The air frictional resistance against a narrow cylinder being displaced transversely with a velocity u creates a force counteracting the displacement which per unit length amounts to $p_1 u$ where p_1 is a certain coefficient representing the influence of the air viscosity. This results in that the frictional moment Q exerted upon a straight pointer projecting perpendicularly to the axis of rotation and having the length a cm. can be calculated with a good degree of approximation from the formula

$$(3)\quad Q=\frac{d}{dt}\int_0^a p_1 x^2 dx = p_1 \frac{a^3}{3}\frac{d\varphi}{dt}$$

in which expression $\frac{d\varphi}{dt}$ is the angular velocity (φ=the angular deflection in radians). In similar manner the frictional moment against the coil can be approximately calculated. If it is desired that the quantity Q calculated from (1) should constitute the fraction $1/m$ (by way of example $\frac{1}{3}$) of the critical damping moment

$$P_k \frac{d\phi}{dt}$$

(relating to the aperiodic limit) and the directional force is set equal to A (in CGS units), the total moment of inertia equal to K and the period of oscillation reduced to the undamped condition equal to T, one has

$$P_k^2 = 4KA = \frac{A^2T^2}{\pi^2} \qquad \left(T=2\pi\sqrt{\frac{K}{A}}\right)$$

thus

$$mp_1 \cdot \frac{a^3}{3} = \frac{AT}{\pi} \text{ or}$$

$$(I)\quad a^3 = \frac{3AT}{\pi m p_1}$$

As mentioned above the value of $1/m$ should be less than the quotient of the electromagnetic damping at closed circuit by the critical damping. The said value is preferably chosen less than 1; by preference the value is equal to $\frac{1}{3}$.

For the root mean square value ϕ of the amplitude of the erratic Brownian fluctuations in absolute angular measure the Equation (1) is valid:

If the value 2.10^{-14} ergs of the molecular energy at room temperature is inserted in Equation (1) the following expression is obtained,

$$(4)\quad \Phi = \frac{2\cdot 10^{-7}}{\sqrt{A}}$$

In order that these small fluctuations may be rendered visible on the reading-off scale, a very high microscope-magnification n must be chosen, preferably such that the magnified average Brownian deflection is of the order of $\frac{1}{10}$ of a division on the scale. The number n, that is the number of divisions on the scale corresponding to a displacement of one millimeter in the object space of course represents here the useful magnification. In other words, the magnification should be so chosen in relation to the optical resolving power of the microscope that $\frac{1}{10}$ of a scale division corresponds to a displacement which is optically accurately discernible. A deflec-

tion of one division then corresponds to the turning angle of

$$\frac{1}{a \cdot 10n}$$

radians. Assuming that the mean Brownian deviation, when magnified, equals $\frac{1}{10}$ of a scale division, one finds

$$(5) \quad \phi = \frac{1}{10} \cdot \frac{1}{a10n}$$

and thus, considering (3),

$$(II) \quad A = 4 \cdot 10^{-10} \cdot n^2 a^2$$

The Equations (I) and (II) determine now in combination the quantities a and A in relation to the chosen values of t, m and n i. e. they serve as basis for the dimensioning of the galvanometer system in order to attain the theoretical limit of sensitivity of these instruments.

I claim:

1. In a galvanometer in combination, a magnetic field system, a moving-coil cooperating therewith, a stiffening rod connecting two opposite points of the coil, elastic suspending means connected with said rod and allowing of small rotary movements of the coil about the axis of said rod, a pointer projecting from the coil, a light passage through the instrument extending perpendicular to the plane of movement of the pointer end, and means for applying microscopic instrumentalities to said light passage for observing the movements of the pointer.

2. In a galvanometer in combination, a magnetic field system, a moving-coil cooperating therewith, a stiffening rod connecting two opposite points of the coil, elastic suspending means connected with said rod and allowing of small rotary movements of the coil about the axis of said rod, clamping means adapted to cooperate with said stiffening rod, a pointer projecting from the coil, a light passage through the instrument extending perpendicular to the plane of movement of the pointer end, and means for applying microscopic instrumentalities to said light passage for observing the movements of the pointer.

3. In a galvanometer in combination, a magnetic field system, a moving-coil cooperating therewith, a stiffening rod connecting two opposite points of the coil, elastic suspending means connected with said rod and allowing a rotary movement of the coil about the axis of said rod, two holding clamps disposed on opposite sides of said rod, and means for adjusting said clamps to be parallel with and symmetrically positioned in relation to the rod so as to engage the rod simultaneously.

4. In a galvanometer in combination, a magnetic field system, a moving-coil cooperating therewith, elastic suspending means carrying said coil and allowing of small rotary movements thereof about a certain position of equilibrium, a short pointer projecting from the coil, a light passage through the instrument extending perpendicular to the plane of movement of the pointer end, an observation objective mounted on the galvanometer and applied to said light passage, and means for adjusting said objective with relation to the pointer end.

5. A galvanometer as claimed in claim 4 characterized in that the observation objective is provided with a central diaphragm which is constructively embodied with the objective in such a manner that it easily may be placed in position on or removed from the objective without opening the instrument or changing the objective setting.

6. A coil galvanometer as claimed in claim 3 characterized in that the holding clamps are pressed by means of springs against a wedge member which is displaceable between the clamps by means of a screw extending excentrically through a rotatable bushing.

7. In a galvanometer in combination, a magnetic field system, a moving-coil operating therewith, a casing enclosing said moving-coil, elastic suspending means carrying said coil and allowing of small rotary movements thereof about a certain position of equilibrium, a pocket projecting from the casing, a pointer projecting from the coil into said pocket, the bottom and lid of the pocket being provided with light apertures, and means for applying microscopic instrumentalities to said light apertures for observing the movements of the pointer.

8. In a galvanometer as claimed in claim 7, a concave adjustable cap screwed into the lid and forming a recess for accommodating an observation objective, the light aperture being arranged at the bottom of said concave cap.

9. In a galvanometer in combination, a magnetic field system, a moving coil, said coil being symmetrical with respect to its rotary axis and co-operating with said magnetic field, suspending torsional wires stretched in opposite directions from the coil and allowing of small rotary movements thereof about a certain position of equilibrium, a pointer projecting from the coil, and means for applying microscopic instrumentalities for reading of the deflection of said pointer, the length of the pointer bearing a relation to the elastic control and the moment of inertia such that the Brownian fluctuations are perceivable at the microscope magnification used, and that the damping moment set up by the air friction is smaller than the electromagnetic damping-moment.

In testimony whereof I affix my signature.

GUSTAF ISING.