

A NULL METHOD OF
PHOTOELECTRIC MEASUREMENT

Sigfus V. Gillis

A Thesis submitted to the
University of Manitoba as a
partial requirement for the
degree of "Master of ^{Arts} ~~Science~~".

April, 1933



INTRODUCTION

Although some forty years have elapsed since the discovery of the photoelectric effect, it is only within the last few years that the photoelectric cell has come into prominence as a practical tool. The thermionic tube is the chief cause of this rapid growth of the practical application of the photoelectric cell since with its aid the very feeble photoelectric currents may be amplified to the stage where they can be used to operate or control practical appliances. So far, however, it has not been applied to the measurement of absorption or to the detection of small changes in the rotation of the plane of polarization of light with any degree of success. This is due to the inherent sources of error in the methods employed except for the balanced bridge circuits which, however, are only suitable for scientific research laboratories because of the high degree of technical skill entailed in their operation. As polarimetry and the measurement of absorption are of such great practical importance it was thought advisable to attempt the construction of a new type of photoelectric instrument which would overcome the disturbing factors suggested above, namely:

- (1) variations of light source,
- (2) variations of photoelectric cell, and
- (3) fluctuations of batteries used to operate the units.

In this paper a null photoelectric method of measuring absorption or the rotation of the plane of polarization of light is described. The treatment is made in two parts, the first of which includes a short historical account of the branches of physics involved, namely, photoelectricity, behavior of light in solutions, and current amplification; while in the second part, the final instrument is considered as well as the numerous devices tested in the process of its evolution.

HISTORICAL

A. PHOTOELECTRICITY

As the derivatives of the word indicate, photoelectricity in its broadest sense involves, the interaction of light and electricity. In this wide sense, it might be used to include several phenomena, more or less related, such as the change of resistance of selenium when light is incident on it, the change in e.m.f. of certain cells containing fluorescent materials as electrolytes when illuminated; or, even the rotation of the plane of polarization of a beam of light when passing through a strong electric field. In this work, however, the meaning of the word will be restricted to the phenomenon of the discharge of negative electricity from certain metals when illuminated by light of appropriate wave length.

In the year 1887, Hertz performed his classical experiments which demonstrated experimentally the electromagnetic waves predicted theoretically by Maxwell. While performing these experiments, he discovered the very important fact that electrical discharges in one oscillatory circuit had a distinct effect upon another similar circuit not directly connected to it. He was using two spark gaps which may be represented by P and S (Figure 1). The terminals of P were suitably connected to an induction coil and the spark discharges across P were oscillatory giving rise to electro-

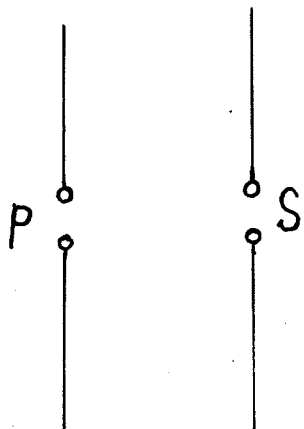


Fig. 1

magnetic waves. To detect these waves he used a suitable tuned circuit containing a spark gap S, the length of which could be adjusted by a micrometer screw. It was known that the longer the spark gap S, the stronger the signal required to give continuous sparking; hence, the maximum

length of S which gave continuous sparking was taken as the measure of the strength of the signal received by S.

In order to make more visible the sparks that occurred at S, Hertz placed his measuring device in a small box. This, he noticed, caused a consistent decrease in the maximum length of the sparks. As the box was made of nonconducting material the effect could not be due to electrostatic or electromagnetic shielding. By removing separately different sides of the box, he discovered that it was only the side that obstructed the view of the inductor spark, P, that caused the change. This naturally suggested to him that some sort of radiation was responsible for the effect and this he tested in several ways. For instance, he screened off the direct radiation from P but used a metal mirror to reflect the light from it upon the spark gap S. This produced the same effect as the direct radiation. Another way he tested this was by interposing numerous opaque and transparent

solids and liquids and noting their effects. From the results obtained, Hertz definitely came to the conclusion that the effect appeared in proportion to the ability of the interposed shield to transmit ultra-violet radiation. He demonstrated further that ultra-violet light from sources other than the inductor spark was just as efficient in increasing the critical length of the detector spark gap S, and that the radiation seemed to have the greatest effect when incident upon the negative terminal of the gap. He noticed also that freshly polished surfaces were superior to tarnished ones.

This outstanding discovery of Hertz attracted numerous investigators. The first one of these to make any significant contribution was Wilhelm Hallwachs. He was convinced that there must be some fundamental effect due to ultra-violet irradiation independent of the spark gaps and the electrical oscillatory discharges. In 1888, he commenced his work on the subject by attempting to simplify Hertz's apparatus and method of procedure. He merely insulated a polished zinc sphere and connected it electrically to a gold-leaf electroscope, and then he investigated the effect of irradiating this sphere, with an arc lamp as source, after having charged it to various potentials. From his observations, he established the following very important results:

1. that when the sphere was negatively charged illuminating

it caused the leaves of the electroscope to collapse indicating a loss of charge;

2. that when it was positively charged irradiation had no appreciable effect;

3. that when it was neutral it acquired a small positive charge under the incidence of the light;

4. that a positively charged insulated body lost its charge when placed in the neighborhood of a negatively charged body which was being irradiated; and,

5. that the magnitude of the effect of illuminating the sphere was dependent, for one thing, upon the material of the sphere. He found that the activity of aluminum, zinc and iron to be in the order recorded.

From these results Hallwachs definitely concluded that under the influence of ultra-violet light negative electricity leaves a body and follows electrostatic lines of force. This phenomenon is often referred to as Hallwachs effect, but more generally as the photoelectric effect.

During the same year two other investigators added some very important facts to the knowledge of this phenomenon. One of these was Righi. He set up a polished plate in front of which he placed a course mesh grid. The plate and the grid were electrically connected with an electrometer which served the purpose of indicating the presence of an electric current in the circuit. When the plate was illuminated

through the grid, the electrometer registered a steady deflection and the plate and the grid came to the same potential. Righi's conclusion was that the original potential difference between plate and grid was a measure of their contact potential. This result, however, has been found to be not true in general. The current was produced under the action of light and he termed it photoelectric current.

Stoletow, the second investigator, used the same arrangement (figure 2) as Righi except that he replaced the electrometer by a sensitive galvanometer and made the important addition of an external e.m.f. which resulted in a

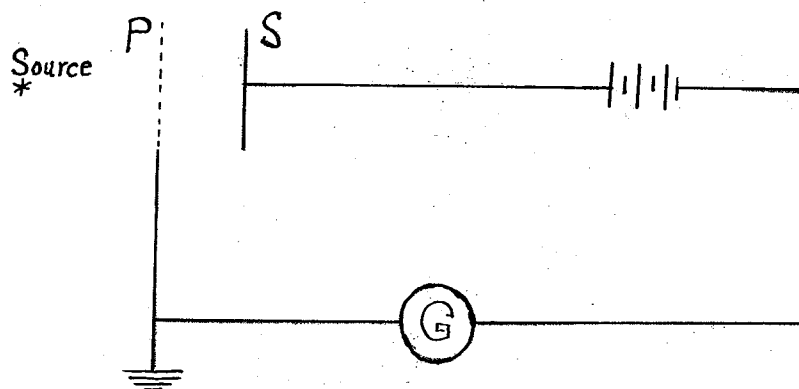


Fig. 2

small but continuous flow of current in the circuit from the grid to the plate in the positive sense, when light was incident on the plate. With this arrangement, Stoletow approached more recent methods for measuring photoelectric effects.

The two famous co-workers Elster and Geitel are responsible for the next great advancement. They noticed that

there was evidently a close relation between the contact potential series of the metals and the photoelectric effect. Of all the metals studied up till then, they observed that the more electropositive the metal, the better the result, and that a response was obtained with light of longer wave length. Consequently, they reasoned that greater sensitivity should result in using still more electropositive metals, for example, the alkali metals. These they proceeded to investigate, particularly sodium and potassium. The chemical activity of these metals, however, made it very difficult to test them experimentally; they react almost instantly with air and water vapor to form oxides and hydroxides which were found to be relatively insensitive. But fortunately Elster and Geitel had previously discovered that an amalgam of zinc was more satisfactory than zinc alone, and they therefore attempted to handle the alkali metals in a similar manner. They discovered that a fresh dilute amalgam of either sodium or potassium was many times more sensitive than the amalgam of zinc, and, what was even more important, it responded to light in the visible region of the spectrum.

Elster and Geitel continued to improve the alkali cell. They first found that hydride crystals of sodium and potassium gave larger effects than the metals themselves. They also passed a glow discharge through one of their potassium cells, which contained hydrogen gas, and discovered that it

greatly increased the sensitivity of the cell. This treatment is now classed as one of the "sensitizing" processes which have marked a new era of development in the art of photoelectrics. The most common method at present is to use thin films of photoelectric metals on various metals. These films possess a characteristic emission quite different from that of the metal, of which they are composed when in bulk; and, the underlying metal as well as the gas deposited on it or on the thin film has a distinct influence. From the different feasible combinations, it is now possible to obtain a cell that has a maximum sensitivity in any desired region from about $8,000 \text{ \AA}$, which is well beyond the red end of the visible spectrum, to below $2,200 \text{ \AA}$ in the ultra-violet. Furthermore, it is possible to obtain cells that are extremely selective in their action, i.e., they respond only to a very limited range of wave lengths within which, however, they are very efficient; these might well be termed "monochromatic" cells.

So far the nature of the mechanism by means of which the negative electricity is transferred from the cathode P to the anode S (fig. 2) has not been considered. A clue to the correct explanation, or rather the one now accepted, was not arrived at until 1897 when Sir J. J. Thomson⁽¹⁾ discovered the electron. Since this new division of matter was found to carry a negative charge, it was naturally suggested as the carrier involved in the photoelectric effect.

Three years after Thomson's discovery, P. Lenard⁽²⁾ performed an experiment which gave positive proof of the validity of this suggestion. He measured the deflections of the photoelectric carriers in a magnetic field of known intensity and obtained a value for e/m , i.e., the ratio of charge to mass for a single particle. The results were in good agreement with the value obtained by Thomson for the electron.

EMPIRICAL LAWS OF PHOTOELECTRICITY

There are two chief laws of photoelectricity. These crystallized gradually from the work of the early investigators. The first law may be stated as follows:

The number of electrons released per unit time at a photoelectric surface is directly proportional to the incident light, provided its quality remains unchanged. This law has been found to be strictly true for a range of intensities varying from zero to full sunlight.

The second law is one which at first sight would be less expected, namely: that the maximum energy of electrons released at a photoelectric surface is independent of the intensity of incident light, but is directly proportional to the frequency of the light.

Just as the classical physics was inadequate for explaining the distribution of energy of a black-body, it likewise failed to account satisfactorily for the release of electrons by radiation. It has been computed that if

a surface is faintly illuminated at the rate of 0.56 erg. per sq. cm. per second, and it is assumed that the illumination is continuously distributed, it would require 200,000 hours for one electron to receive sufficient energy to be ejected from the surface. However, experiments reveal that they are emitted in periods as short as one ten millionth of a second.⁽³⁾ This discrepancy between theory and fact was not removed until 1905 when Albert Einstein proposed that this photoemissive phenomenon could be accounted for by adopting Planck's quantum theory of radiation on the basis of which the interchange of energy between two "systems" was not a perfectly continuous process as had hitherto been supposed, but rather a discontinuous one in which the minimum bundle or quantum of exchange was given by $h\nu$, where h is a universal constant and ν is the frequency of the radiation. Einstein deduced an equation which according to the data at his disposal indicated results of at least the correct order of magnitude by assuming that when a quantum of energy $h\nu$ reacted with an electron, the latter would acquire the total quantum and be released in possession of an equivalent amount of energy. This equation will be referred to later.

The experimental relation found between photoelectric current and the potential applied to the emitting electrode is particularly instructive. This was first investigated by Lenard⁽⁴⁾ but has since been investigated by numerous other experimenters. The source of illumination was strictly

monochromatic and its intensity could be varied in a known manner. The experimental results are shown in Fig. 3, below. The different intensities are indicated by L_1 , L_2 , L_3

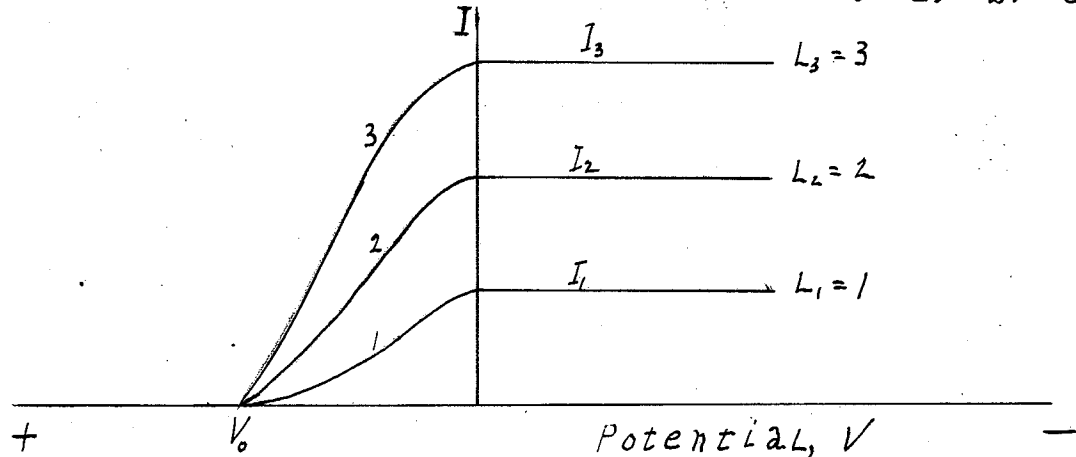


Fig. 3

and their relative values are as 1:2:3 respectively. Let us first examine the relation between I and V , when the intensity is L_1 , and then compare the others to this one. The first thing to be noted is that there is no photoelectric current observed when the positive potential is greater than a critical value V_0 . Then as the potential is gradually decreased the current rises slowly at first and then more rapidly until it reaches a maximum value when $V = 0$, and no further increase results in making V negative. I_1 represents the maximum current which results from an illumination of intensity L_1 . If the intensity is doubled, the critical potential V_0 is exactly the same but the maximum value of current is exactly doubled. Similarly if the intensity is trebled the resultant maximum current is trebled but the

critical potential is still unchanged. Thus, we have, calling the maximum current I_m for a given intensity of illumination L , that I_m is proportional to L , or the first law of photoelectricity.

To interpret these results it is necessary to assume that the electrons are emitted from the surface of the electrode with a range of velocities varying from zero to v_m . Since $\frac{1}{2} mv^2$ is the kinetic energy which an electron, mass m , possesses when it emerges with a velocity v , it is evident that only those electrons will reach the receiving electrode which have a value of $\frac{1}{2} mv^2 > Ve$, where V is the potential difference between the electrodes and e is the charge on the electron. Since no current is observed when the applied voltage is greater than V_0 , the maximum velocity V_m possessed by any electron is given by

$$\frac{1}{2} m V_m^2 = V_0 e .$$

On the other hand, when $V = 0$, any electron which emerges with a velocity greater than zero will reach the receiving electrode.

Strikingly different is the form of the curves which result when the photoelectric current is determined for several different monochromatic radiations of wave length $\lambda_1, \lambda_2, \lambda_3$, etc., as a function of the applied voltage V falling on the emitting electrode.⁽⁵⁾ This is shown in Fig.4. The intensities of illumination for each wave length have been so adjusted that the maximum value of I_m is the same

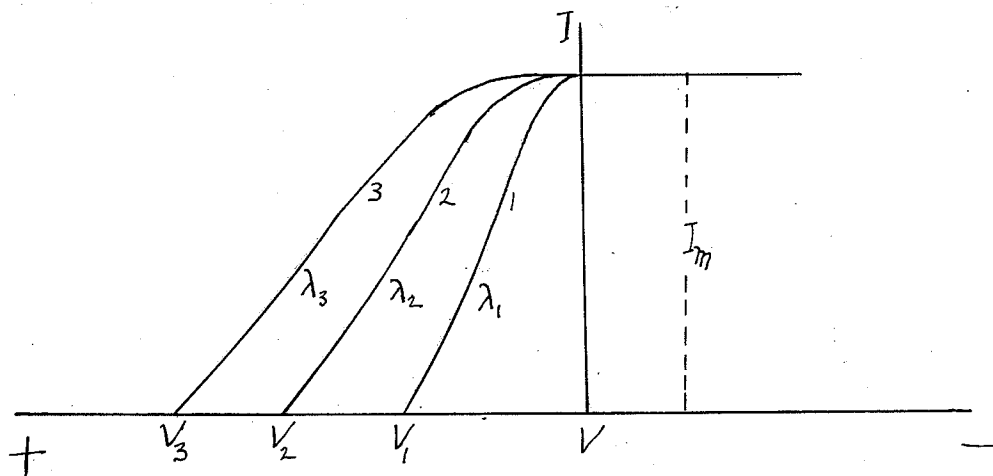


Fig. 4

Dependence of the Photoelectric Current on the Wave Lengths of the Exciting Light; $\lambda_1, \lambda_2, \lambda_3$.

in each case. Since $\lambda_1 > \lambda_2 > \lambda_3$ and $V_1 < V_2 < V_3$ where V_1, V_2 and V_3 are the corresponding critical retarding voltages, it shows that the shorter the wave length the greater is the retarding voltage V_0 which is just necessary to prevent the electron with the highest velocity from reaching the receiving electrode. This phenomena can be expressed in terms of the maximum kinetic energy of photoelectrons, given by $\frac{1}{2} m v_m^2 = V_0 e$; namely, that it increases with decreasing wave length.

Millikan⁽⁶⁾ plotted a curve between $V_0 e$ or $\frac{1}{2} m v_m^2$ and the corresponding frequency and he found that a very simple linear relation resulted as is shown in Fig. 5. It will be seen that this line has an intercept ν_0 the experimental meaning of which is that light of frequency less than ν_0 cannot cause the emission of electrons from the photoelectric surface concerned. The equation of the line may be written:

$$V_0 e = \frac{1}{2} m v_m^2 = h(\nu - \nu_0)$$

$$\text{or} \quad \frac{1}{2} m v_m^2 = h\nu - W_0$$

where h is the slope of the curve and W_0 is written for $h\nu_0$.

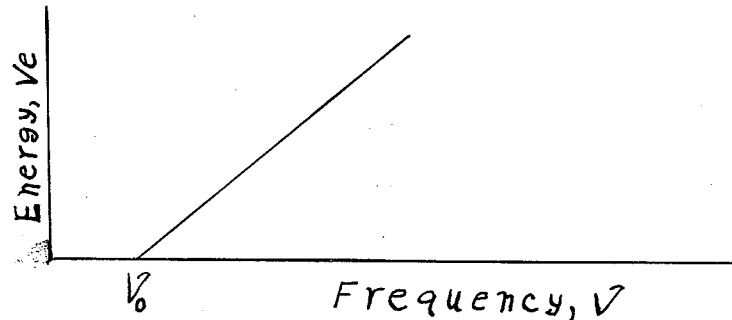


Fig. 5.

This is one of the fundamental laws of physics, and is generally referred to as "Einstein's photoelectric equation", since he was the first one to deduce it on theoretical basis. The work of Millikan, referred to above, gave it complete experimental verification.

Since the dimensions of the left-hand side of the equation are those of energy, it follows that both terms on the right-hand side stand for quantities of energy. Now h is the slope of the curve and is found to be the same for all emitting electrodes, hence the quantity of energy $h\nu$ depends solely on the frequency of the incident light. W_0 , on the other hand, is found to be a quantity of energy the value of which is dependent on the emitting surface; it is the least amount of energy which the electron expends in escaping from the attracting forces at the surface of the metal and is generally referred to as the "work function"

of the metal. The Greek letter ϕ is used to represent this and it is generally expressed in volts for the charge on the electron is constant, and therefore the energy acquired (V_e) by an electron in falling through a certain potential difference V is simply dependent on that difference. The value of the energy $h\nu$ on the contrary is dependent solely on the frequency ν of the incident light. It is the amount of energy which the electron receives while $\frac{1}{2} m v_m^2$ represents the energy with which only the most favorably situated electrons emerge.

This equation applies equally well to the electrons emerging with lower velocities, the only difference here being that they are less favorably situated and consequently expend more energy, W_0 , in the process of breaking through the boundary of the metal.

Although it is not known how radiation causes the expulsion of electrons from metals or why it is always transferred in bundles of finite size, yet the law of the transference of energy, when stated in terms of wave-lengths, is very simple. It is expressed by the relation

$$E_\lambda = \frac{1234}{\lambda}$$

where E_λ is the amount of energy, measured in volts, which the electron acquires from light of wave length λ in $m\mu$ ($1 m\mu = 10^{-7}$ cm). Thus the shorter the wave length of the light, the greater is the energy that the electron acquires.

This is expressed quantitatively for a few wave lengths in the visible spectrum, Table I.⁽⁷⁾

<u>Table I</u>		
Colour	λ	E_{λ} (quantum voltages)
Extreme red	750 m u	1.65 volts
Red	650 "	1.82 "
Yellow	580 "	2.13 "
Green	520 "	2.37 "
Blue	460 "	2.68 "
Extreme violet	400 "	3.08 "

It is instructive to compare this table to the one below which gives the work function for a few metals along with the threshold wave lengths in the third column.

<u>Table II</u>		
Metal	ϕ (work function)	λ (threshold)
Pt.	6.30 volts	196 m u
W	4.54 "	272 "
Cd	3.94 "	313 "
Na	2.05 "	600 "
K	1.90 "	650 "
Rb	1.69 "	730 "
Cs	1.54 "	800 "

In order that light shall liberate electrons from a metal the energy received by the electrons from the light must be equal to or greater than that necessary for their emergence, i.e., the quantum voltage E_{λ} in column 3, Table I, of the light must be equal to or greater than the work function ϕ of the metal which is given in column 2, Table II. The photoelectric threshold λ given in Table II expresses

the wave length, the quantum voltage of which is equal to the work function of the metal; it is defined as the longest wave length of light which is capable of producing a photoelectric effect in the particular metal concerned. If the quantum voltage of the light is greater than the work function of the metal the electron acquires more energy than is necessary for its emergence. The excess energy causes the electrons to emerge with a certain initial velocity.

Thus, in practice if the electrodes of the cell are contained in an evacuated vessel, i.e., a vacuum cell there will be a linear relation between the photoelectric current and the intensity of the light source if its quality is unchanged. In case of a gas-filled cell, on the other hand, this linearity does not exist because of the production of an increased number of electrons by collision, a phenomenon which will be described later.

B. Behavior of Light in Solutions

The chief modifications produced in light by passing through solutions are, decrease in intensity, i.e., absorption, and, in case of plane polarized light, possible rotation of the plane of polarization. We shall consider these phenomena separately under the headings of absorption and polarimetry.

(a) Absorption

For a beam of given wave length, the fraction by which the intensity is reduced in passing through a small distance dx of solution is the same at all depths. This may be written in mathematical form as,

$$\frac{dI}{I} = -a dx$$

where dI is equal to the change in intensity I in the small distance dx and " a " is a constant depending both on the nature of the substance and the wave length of the light employed. The negative sign is used to indicate that the change in I is a decrease.

The above formula applies only if dx is so small that the corresponding dI is an infinitesimal. It may therefore be integrated and we have at once

$$\log(I/I_0) = -a x$$

or

$$I = I_0 e^{-ax}$$

where I_0 is the intensity of the incident beam; I , the intensity after it has traversed a thickness x ; e , the base of natural logarithms, and " a " the same constant previously mentioned and now defined as the coefficient of absorption. This coefficient gives the rapidity with which I diminishes. If " a " is constant over the visible region of the spectrum, the absorption is said to be general. If, on the other hand, it varies with the wave length, the relative intensities of the different wave lengths in the original light are changed. This produces colour, and absorption under these conditions is said to be selective.

(b) Polarimetry.

Since the basis of polarimetry is plane polarized light, it is desirable to make a brief study of its chief properties.

The foundations of the theory of polarization which holds to the present time were laid by Young and Fresnel in their conception of light transmission by transverse wave motion. Fresnel perceived at once the obvious explanation of polarization that would be offered by supposing that the vibrations were restricted to a definite unchanging path at right angles to the direction of propagation. This is what today is known as the plane of polarization. Now a transverse vibration may be resolved into two component vibrations at right angles in the same plane. It may be supposed

that a crystal of calcite has an inherent power of resolving light vibrations in this way, and a separation of the two rays would be effected if it is supposed that one set of vibrations proceeds through the crystal with a different rate of propagation from that of the perpendicular set. Thus a very simple explanation of polarization and double refraction is obtained.

The most effective and convenient method of procuring plane-polarized light is by double refraction and the best way of obtaining this is by means of a crystal of Iceland spar (a form of calcium carbonate). It is found in considerable masses of great purity and transparency. The fundamental crystal form of this mineral is the rhombohedron, i.e., it is bounded by six parallelograms the angles of which are $101^{\circ} 55'$ and $78^{\circ} 05'$ respectively.

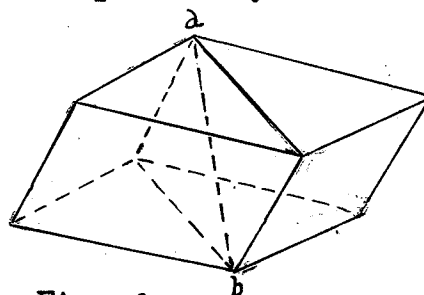


Fig. 6

Two solid angles a and b diametrically opposite are contained by three obtuse angles, while each of the remaining four is bounded by one obtuse and two acute angles. The direction making equal angles with the faces at the summits of the obtuse solid angles is called the axis of the crystal. Thus

containing this axis is called the principal section of the prism. The prism is then cut in two in such a way that the dividing plane GKCL is at right angles to the principal section. The two halves are then cemented together in their original position by a thin film of Canada Balsam. The significant fact about this Canada Balsam is that its refractive index is greater than that of the extraordinary in the spar but less than that of the ordinary. Now total reflection occurs in passing from a more to a less refracting medium only. Hence if a beam MN of unpolarized light strikes the face ABCD it will on entering the crystal be divided into the ordinary ray NO and the extraordinary ray NQ since it is travelling in a direction inclined to the optic axis, and if the inclination of NO to GKCL exceeds a certain value this ray will suffer total reflection while the extraordinary ray will pass on through the crystal and emerge at Q. The Nicol prism thus yields a pure beam of plane-polarized light as the prism is mounted in a tube blackened on the inside so that the reflected beam is absorbed.

In practice the Nicol prisms are almost invariably used in pairs: the first being used to obtain a beam of plane-polarized light while the second serves the purpose of examining or analyzing this beam. The former is called a polarizer and the latter an analyzer. The intensity of the emergent beam is given by Malus's cosine squared law, and the

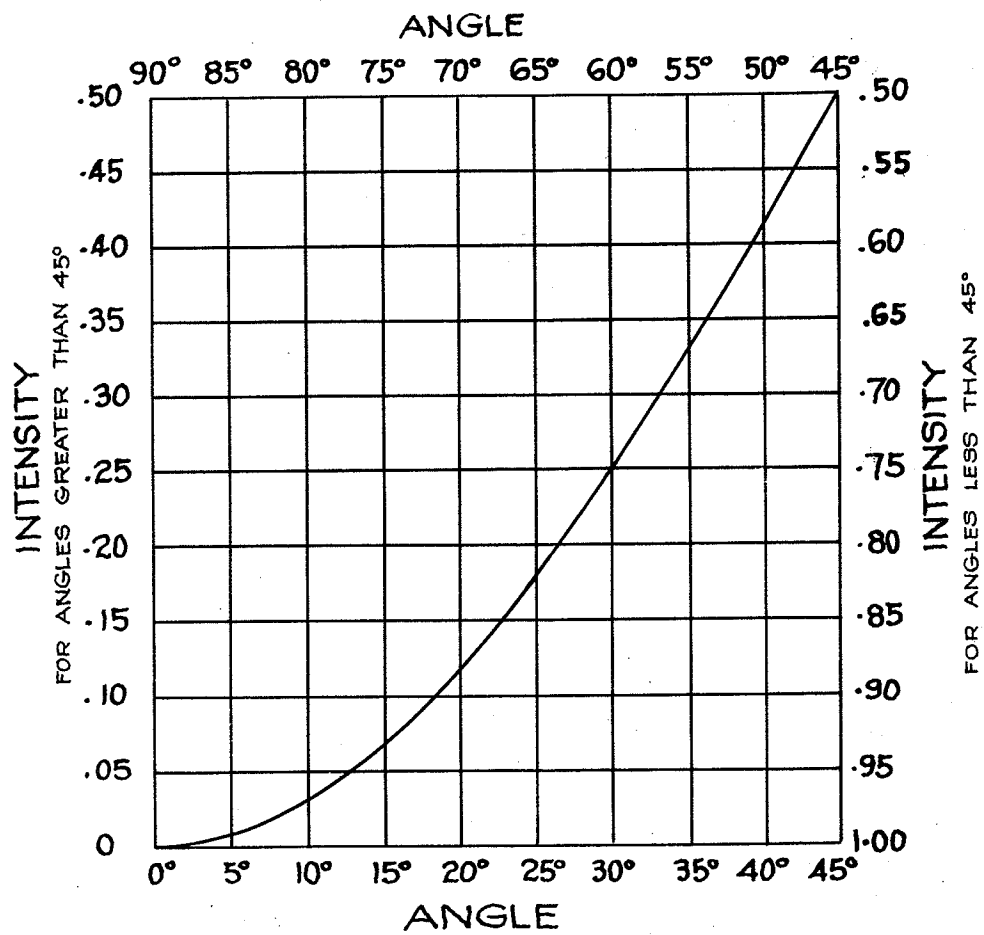


FIG. 8

well known relation between the intensity and the angle between the principal sections of the Nicols is given in Fig. 8.

In 1811 Arago observed that the effect produced when a plate of quartz, cut perpendicular to its axis was placed between a polarizer and an analyzer differed from that caused by a plate of mica in the same place. Biot, however, was the first to point out, in the following year, that a rotation of some kind was involved. He showed also in 1815 that this property was exhibited by turpentine and a number of other substances. An extended examination of polarization has shown that it is possessed by (1) crystalline quartz along the optic axis; (2) certain liquids such as turpentine as well as solutions of sugar, tartaric acid, etc., and (3) certain isotropic substance when placed under strain. The name rotatory dispersion has been given to this property and substances which produce this effect are called optically active.

Concerning the actual amount of rotation, the following simple laws have been found experimentally:

(1) in case of quartz and pure liquids, for a fixed wave length, the angle of rotation is directly proportional to the thickness. For solutions, the angle for a given thickness is proportional to the concentration of the optically active substance.

(2) for a fixed thickness, the angle of rotation varies roughly inversely as the square of the wave length.

To compare optical activity of different substances a unit must be adopted. This is done by defining the term specific rotation as the ratio of the angle of rotation for a thickness of 10 cm. to the density of the solution in grams per cc.

Since the angle of rotation of an optically active substance in solution is proportional to the concentration, a quantitative means is thus provided for studying the strength of such solutions and therein lies the great commercial application of polarimeters particularly in the case of sugars. Polarimeters are given the special name of saccharimeters when used to test sugars. In the simplest form polarimeters consist simply of a polarizer, an analyzer whose exact position can be read on a scale, and between the two a tube with transparent ends containing the optically active solution. In this form the analyzer is set for extinction before and after the introduction of the solution, the difference in the two readings being, of course, equal to the angle of rotation. The position of exact extinction, however, cannot be set exactly enough for accurate measurements, and, in actual practice, settings with the visual polarimeters are generally made by what is called the brightness half-shade method. In essence this consists in

altering the simple polarimeter arrangement so that at least two contiguous parts of the field of view are obtained and the final setting of the analyzer being made when these are of equal brightness. The underlying principle of this is that the eye, under favorable conditions, can detect very small differences of intensity. It was first employed by Jellet⁽⁸⁾ in constructing an analyzer which is called in his honour Jellet's Prism. In this prism, however the angle between the planes of polarization, i. e., the "half-shadow" angle, is fixed. This is a disagreeable feature since the size of this angle for maximum sensitivity depends on the intensity of the light source. If this angle has been made too small the prism may become no better than ordinary Nicols since the brightness of the field at matching point compared with the maximum brightness obtainable is proportional to $\sin^2 \left(\frac{\alpha}{2} \right)$ where α is the half-shadow angle. Further, it is not desirable to make the angle too large since then the sensitivity is reduced according to Weber's law which states that

$$\frac{\Delta I}{I} = \text{constant}$$

where ΔI is the least perceptible increase in the brightness of one of two contrasting patches of original brightness I .

This defect is eliminated in the polarizing system of Lippich which is in general use in the best polarimeters. In this system the half-shadow angle may be varied, since

two small auxiliary Nicols B and C (Fig. 9) making any desired angle with the polarizing Nicol A, are employed to produce the desired divisions in the field. As is shown in

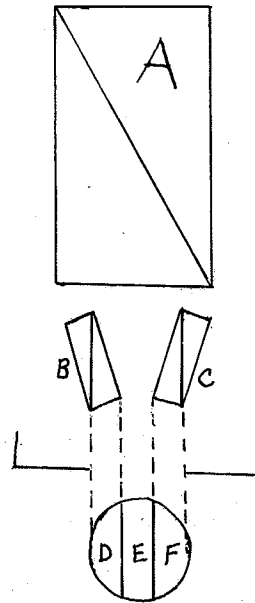


Fig. 9.

Fig.9 the resulting field (DEF) is divided into three parts.

The auxiliary prisms must be mounted with extreme care, and their edges must be sharp and free from flaws in order to get distinct separating lines in the field. With the most sensitive conditions and a source of light so bright that the half-shadow angle may be reduced to 1° , the mean error may be reduced as low as $\pm 15''$ of arc.⁽⁹⁾ These conditions, however, are very hard to realize in practice so that the mean error is generally considerably larger.

C. AMPLIFICATION

Even the very best gas-filled photoelectric cells yield currents only as great as 100 microamperes per lumen of light flux.⁽¹⁰⁾ Many types of cells may yield only one hundredth or one tenth this amount. In most applications of the photoelectric cell the intensity of the light available is low (e.g. less than 1/10 lumen) so that it is essential to amplify the photoelectric current many times before it may be utilized. Amplification may be accomplished either within or outside the cell.

(1) Internal Amplification

Internal amplification is effected by using a gas-filled cell, the result being that the primary photoelectric current is amplified by the production of an increased number of electrons according to the following process. When a slowly moving electron collides with a molecule, they follow the laws of elastic bodies. If, however, the electron is moving fast enough and makes a sufficiently direct impact on a gas molecule, it may detach a second electron from the molecule leaving a positively charged ion. The energy required to sever an electron from a molecule or to ionize it, is a definite property of the molecule called its "ionization potential". It usually lies between 10 and 25 volts and is generally represented by ϕ . Thus, in order to

ionize, the kinetic energy which the electron possesses must be greater than that which is necessary to ionize a molecule of the gas.

Every time an ionization collision takes place, two electrons are present in the gas in place of one. If the gas is placed in an electric field, as is the case when a potential is applied on the cell, both electrons will move to the anode, while the positive ion moves to the cathode. Hence the anode receives a charge equal to twice that on an electron; the cathode receives an equal and opposite charge, represented by the charge on the primary electron which it loses and that on the positive ion which it gains. Supposing that each electron ionizes n times in passing through the gas, the current through the cell would be $(n + 1)$ times that carried by the primary electron, provided no recombination took place.

By assuming that an electron loses all its energy when it collides and fails to ionize, it is easy to prove (11) that for two plane electrodes, distance d apart and the space between them filled with a gas at pressure p , that

$$n^1 = \frac{pd}{\lambda_0} f\left(\frac{E\lambda_0}{pd}\right)$$

where

E = potential difference between plates,

λ_0 = mean free path multiplied by the pressure of gas and n^1 represents the actual number of ionization collisions, i.e., it is the factor that determines the amount

of amplification.

There are two deductions from the above equation, namely

- (1) that n^1 increases with E if pd is constant, and
- (2) that if E is constant there is a value of pd for which n^1 is a maximum. The value of pd for maximum n^1 is determined by $\frac{E\lambda_0}{\phi}$ and is found to be numerically of the same order of magnitude.

As regards the first deduction, a logical conclusion would be that any desired degree of amplification could be attained by merely increasing E sufficiently. In practice, however, the action of the positive ions is found to set a definite limit to the magnitude of E which may be usefully applied. They affect the current in two ways. First, they cause the liberation of electrons from the cathode independently of the photoelectric emission; second, their presence in the neighborhood of the cathode increases the field there in virtue of the charge that they carry. As E is increased and with it the number of positive ions, a stage is reached at which these ions, in their turn, produce at the cathode secondary electrons as numerous as the primaries. The current will then continue to flow even when the light is turned off, as the liberation of the primaries is no longer necessary to its continuance. This condition is accompanied by a visible glow in the gas and consequently the potential at which it occurs is called the glow potential.

It represents the highest potential that can be applied usefully to a photoelectric cell since at this stage its current ceases to vary regularly with the illumination. Furthermore, if the voltage is increased above the glow potential, and the current through the cell is not limited by the exterior circuit, the glow discharge may turn into an arc, characterized by the heating of the electrodes to incandescence. This condition would destroy the cell immediately, so that it is desirable to insert a protective resistance of at least 10,000 ohms in series with the cell.

The gas most commonly used in photoelectric cells is argon both because of its low ionization potential and because it does not easily form negative carriers, i. e., an electron attached to a neutral molecule. When an alkali metal is used as the photo-sensitive metal the gas must be one of the inert gases, i.e., helium, neon, argon, krypton, and xenon, because of the chemical activity of these metals.

(2) External Amplification

The usual way to amplify photoelectric currents is to do it outside the cell. This is accomplished in all modern methods by using the three electrode type of thermionic valve. Essentially it consists of a highly evacuated vessel V, (Fig.10) containing a cathode F, usually in the form of a filament which can be heated by passing a current through it, an anode A, and a discharge controlling-electrode G,

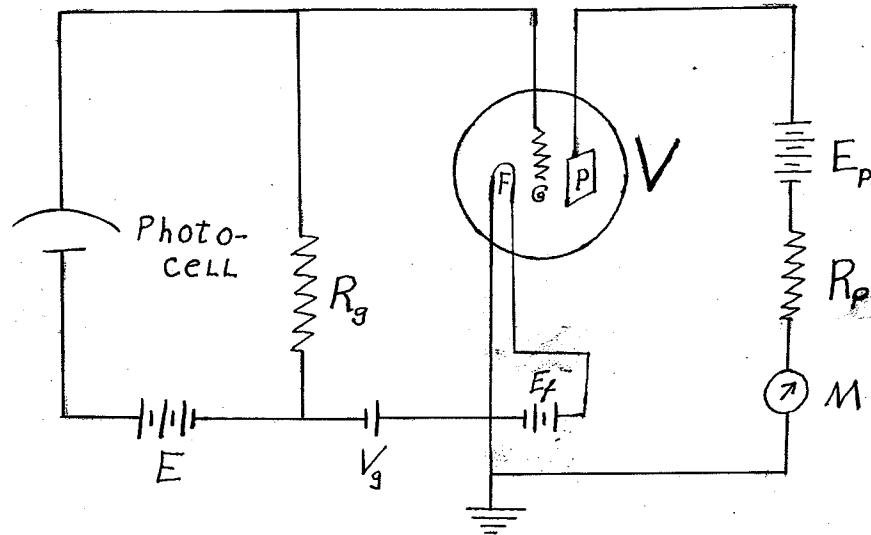


Fig. 10

placed between the anode and cathode and generally taking the form of a wire mesh or grid. When the filament is heated it emits electrons solely in virtue of the kinetic energy of the "free" electrons in the metal as was shown by O. W. Richardson⁽¹²⁾ in 1901 when he gave the first true explanation of the mechanism involved. Richardson designated this emission of electrons as thermionic emission and consequently the title thermionic valve for the above device as its functioning depends primarily upon this emission of electrons from the heated filament. Now if an external e.m.f., E_p , is placed in the anode or plate circuit as shown in Fig. 10 the electrons will be attracted to the plate and a current will flow in the circuit, the magnitude of which will be indicated

on the current-measuring instrument M. If the grid were not connected in any way to earth as shown, the result would be that some of the electrons would accumulate on the grid and charge it up negatively to a potential sufficient to block their passage to the plate entirely. Since the value of the resistance R_g controls the rate at which the electrons "leak" off the grid, it is generally called a grid leak resistance.

Due to the proximity of the grid to the filament an applied potential of say one volt on it may have many times as much influence on the value of the plate current as the same potential on the plate. The number of volts change required on the plate to produce the same effect on the plate current as caused by one volt change on the grid is defined as the voltage amplification factor of the tube and is conventionally represented by the symbol μ . Hence if the photoelectric cell is placed in the grid circuit, or the input circuit as it is called, the photoelectric current may be measured on an amplified scale in the plate circuit.

Another very important property of a thermionic tube is the expression for the ratio of the change in the plate current (di_p) for a given change in the grid potential (dE_g). This ratio has been given the special name of "mutual conductance" and is often designated by the letter M.

Thus we have,

$$M = \frac{di_p}{dE_g} = \frac{\frac{di_p}{dE_p}}{\frac{dE_g}{dE_p}} = \frac{\frac{1}{Z_p}}{\frac{1}{\mu}} = \frac{\mu}{Z_p}$$

where Z_p is the plate impedance of the tube.

Now in order to obtain a clear understanding of the operation of a thermionic tube, the best procedure is to deduce equations representing the relationship of the variables involved and also indicating their significance. Nottingham's⁽¹³⁾ analysis is very good and is somewhat as follows.

When it is necessary to represent the characteristics of a thermionic tube over a very narrow range of grid and plate potentials, the following simple equation nearly always gives a sufficiently close representation:

$$i_p = \frac{1}{Z_p} (E_p + \mu E_g + E_0)$$

where i_p = plate current,

E_p = plate potential,

E_g = grid potential,

E_0 = constant,

μ = voltage amplification factor, and

Z_p = plate impedance.

In using this very simplified form of the tube equation, we must remember that it can be used only in those cases in

which E_o , μ , and Z_p can be treated as constants which are independent of E_p and E_g for the limited range of their variation. If we define the sensitivity (S) to voltage as the change in plate current for a small change in grid potential, we have:

$$S = \frac{di_p}{dE_g} = \frac{\frac{\mu}{Z_p}}{1 + \frac{R_p}{Z_p}} = \frac{M}{1 + \frac{R_p}{Z_p}} \quad (1)$$

From this equation, we see that when R_p , the external plate resistance, is small compared with Z_p the sensitivity is equal to the mutual conductance M , but if R_p is not small then the sensitivity is less than M because Z_p is always positive.

In many of the applications of thermionic tubes, we are not interested directly in the change in plate current with a change in grid potential but in the change of some current such as the photoelectric cell (Fig. 10).

For the grid circuit we have the equation,

$$E_g = V_g - R_g(i_g - i)$$

where V_g = "C" battery potential,

R_g = external grid leak resistance,

i_g = grid current, and

i = photoelectric current.

If we differentiate this equation with respect to "i",

we get,

$$\frac{dE_g}{di} = R_g - R_g \frac{di_g}{dE_g} \times \frac{dE_g}{di}$$

But $\frac{dE_g}{di_g}$ may be defined as the grid impedance (Z_p).

Hence by rearranging we find,

$$\frac{dE_g}{di} = \frac{R_g}{1 + \frac{R_g}{Z_g}} \quad (2)$$

Combining equations (1) and (2), we have,

$$\frac{di_p}{di} = \frac{M}{1 + \frac{R_p}{Z_p}} \times \frac{R_g}{1 + \frac{R_g}{Z_g}}$$

This equation gives the sensitivity as the current amplification of the one tube amplifier in terms of constants of the circuit. For example, we readily see that the higher the value of R_g , the greater the resulting amplification. Hence, in practice, R_g should be large enough to bring about maximum amplification without introducing instability. This condition is chiefly the result of the conductances of the insulation and the irregularities of the tube which sets a definite limit to useful amplification. When very high resistances are employed, however, an appreciable time is required for the current to reach a steady value. This explains

THE INSTRUMENT

There has been only one photoelectric method applied to polarimetry and absorption that has received any general acceptance. This is known as the "standard" substitution method and consists simply of altering the intensity of the light incident on the photoelectric cell until a certain predetermined deflection is obtained on the current-measuring device both before and after the substance under observation has been introduced between the set of Nicols used to control the intensity of the light. As the operation requires considerable time to execute, the accuracy of the method is dependent upon the constancy of

1. the source of illumination,
2. the photoelectric cell, and
3. the amplification system.

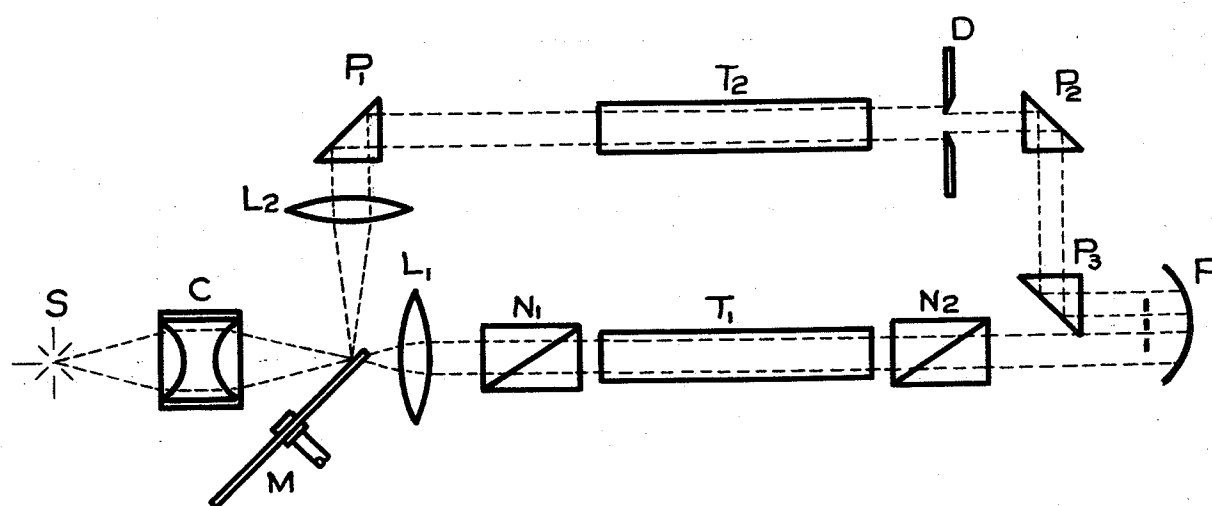
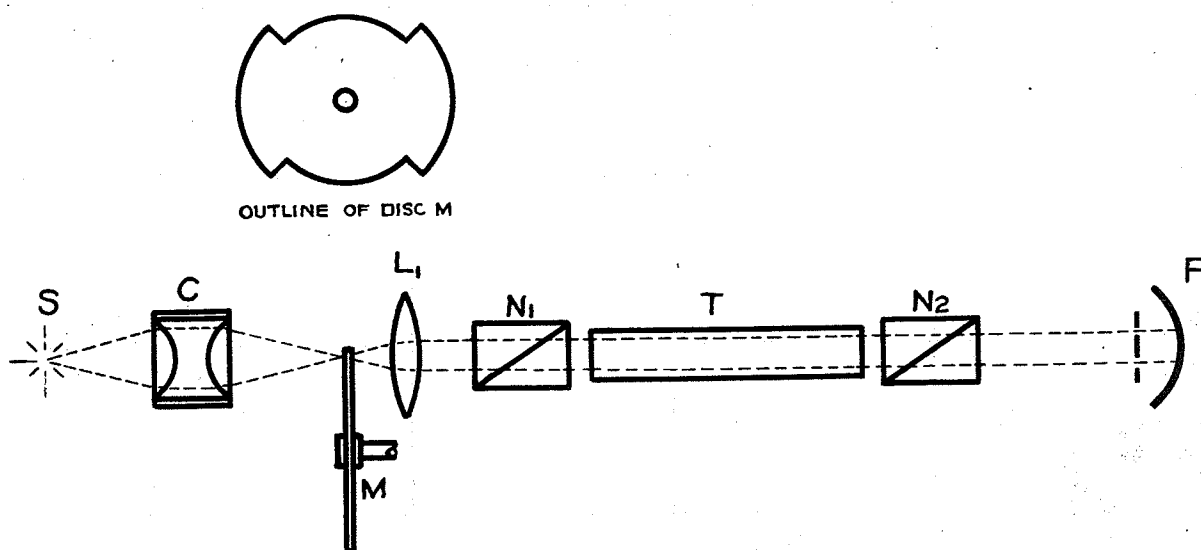
The output in lumens of an incandescent lamp, constructed more elaborately than most commercial lamps, can be maintained constant to 1 part in 400 if the voltage across it is controlled to 1 part in 1,500.⁽¹⁴⁾ This is not easy to realize in practice, the variations of most sources being considerably greater. The changes of emission of a gas-filled cell during use, however, are more serious. These are due chiefly to the formation of gas films on the cathode which largely determines its emission or to the accumulation of charges on the walls which alters the distribution of the

field and consequently the current produced. The impact of the positive ions on the cathode is the main cause of the changes in its surface but the incident light, if intense, may also produce this change, as the walls may become heated appreciably and thus cause a change in the distribution of the film and the charges. Furthermore, with a gas-filled cell, a linear relation does not exist between the current and the light flux and in all such cells the current, under a given illumination, depends somewhat on its previous history. For these reasons, a well-made vacuum cell must be employed since its emission is very constant and also directly proportional to the light flux. The output of a vacuum cell per lumen of light flux, however, is only a small fraction of that of a gas-filled cell as has been pointed out. The photoelectric current must consequently be greatly amplified externally and this is very difficult to accomplish with direct currents.

As regards the irregularities due to the "amplification system", it is evident that changes in the potential between the grid and filament of the amplifying tube will be amplified in the same way whether caused by a current from the photoelectric cell or by a change in the voltage of the batteries feeding the tube. The constancy of the grid bias battery is most important but that of the filament battery is scarcely less so, variation of the anode voltage is

somewhat less important since it is reduced effectively by the amplification factor of the tube. Slow regular variations of the voltages as the batteries run down are unavoidable but these are unimportant compared with rapid and irregular changes.

The optical arrangement of the first device, tried to overcome these sources of error as well as to introduce some new desirable features, is shown in Fig. 11. It was simply the usual arrangement with the addition of a disk M provided with evenly spaced rectangular slots at the periphery. This disk was mounted on the axis of a synchronous motor and interposed in the optical path at the position of the image of the source, S. The output of the photoelectric cell P was thus converted into pulsations by the mechanical interruptions of the rotating sectored disk so that advantage could be taken of the superiority of alternating over direct current amplification. In multi-stage direct current circuits, it is necessary to have a separate voltage supply for the plates of each stage in order that the grids may be insulated from one another. These separate supplies introduce instability due to their individual variations and render such systems of theoretical value only. In case of alternating current amplifiers, on the other hand, it is possible to use interstage couplings which prevent the plate voltages from being impressed directly on the grids of subsequent tubes



and consequently a single voltage supply may be used for all valves, e.g., the arrangement shown in Fig. 16.

The photoelectric cell was coupled to the thermionic valve as shown in Fig. 14. It was an arrangement similar to that used by Arthur C. Hardy,⁽¹⁵⁾ in investigating reflecting surfaces. The cathode of the cell was connected directly to the grid of a UX-222 used as a triode. In total darkness, the potential of the grid is the same as if the photoelectric cell were disconnected, that is, free grid potential. When light is incident on the cell, however, the grid potential increases until the grid current equals the photoelectric current. The variation of the plate and grid currents with grid potential were obtained as shown in Fig. 13 for the UX-222 valve with 22.5 volts on the plate. The cell and valve were contained in a separate compartment covered with a conducting material which served as an electrostatic shield.

The presence of the alternating current was indicated by a hum in the telephone receivers connected in the plate circuit of the valve. On crossing the Nicols this hum naturally stopped and the point at which it just became audible was taken as the position of balance. The difficulty experienced with this arrangement, as anticipated, was that the hum ceased over a considerable range (about 2°) and that it was difficult to judge just when it became audible since the intensity of the light transmitted through the Nicols



increases very slowly with the angle of rotation at this stage (Fig. 8).

The sensitivity of this method was consequently not very satisfactory as is shown by the set of readings given in Table III below.

Table III

85° 25'	85° 30'
85° 40'	85° 31'
85° 11'	85° 13'
85° 23'	85° 02'
85° 38'	85° 50'

The mean square error of these readings is $\pm 4' 48''$ which is too large to be permissible.

In an endeavor to increase the sensitivity, the optical device shown in Fig. 12 was arranged, i. e., a double compensating path was secured by setting the sectorized disk M at an angle of 45° to the axis of the light beam and having the closed sectors of some good reflecting material so that the light falling on these would be reflected and, after being rendered parallel by the lens L_2 , incident on the photoelectric cell P by means of right angle prisms P_1 , P_2 , and P_3 . Thus we have two beams of light alternately incident on the photoelectric cell and if these are of equal intensity its output will evidently be a continuous current and as a result no hum would be heard in the receivers. Hence, with

this arrangement, the magnitude of the angle between the planes of the Nicols, at which the hum ceases, can be chosen by varying the intensity of the light in the reflected beam by means of the variable shutter D. The variation of the intensity of the transmitted light with the angle between the Nicols is practically constant from 30° to 60° (Fig. 8) so that it is immaterial where the position of balance is taken between these limits. In this range, a small rotation of the plane of polarization of one of the Nicols causes a far greater change in the intensity of the light transmitted than does the same rotation when the two are crossed, or nearly so. The sensitivity of this arrangement should therefore, be increased by a corresponding amount. It would, furthermore, eliminate the effect of variations of the light source, the photoelectric cell, and the batteries since the frequency of alternation of the two beams could be made of much higher order than the rate at which these factors vary. A gas-filled caesium photoelectric cell was consequently used so that advantage would be derived from internal amplification. Another desirable feature about this optical arrangement is that it renders the instrument equally applicable to the measurement of either absorption or rotation of the plane of polarization of light by an optically active solution. Thus, if the former were desired only one tube would be used and placed

in the position occupied by tube T_1 (Fig. 12). The adjustment for balance would then be performed both before and after the tube was filled with the liquid under consideration, the difference of the two readings giving a measure of the relative decrease in intensity of the light due to absorption. If, on the other hand, the specific rotatory power of a substance were desired the two similar tubes T_1 and T_2 shown in each arm, (Fig. 12) would be utilized. The two adjustments would be made, as above, one before and after the tubes were filled with the optically active solution. Absorption in the two tubes would balance and consequently the difference in the two readings would be a direct measure of the amount that the plane of polarization has been rotated by the solution in tube T_1 .

When the device was tested, however, it did not operate according to theory. The cause of the discrepancy was a regular periodic click in the receivers even when the two beams were evidently of equal intensity. This click was considered to be the result of a change in intensity of the light beam when shifting over from one arm to the other, that is, even when these were of equal intensity, the rate at which one decreased was not equal to the rate at which the other increased. Due to this disturbing factor it was not possible to determine when the two were of equal intensity.

In attempting to eliminate this click several disks were constructed and tested. The first of these was of glass containing alternate, equiangular, closed and open segments. To obtain the open segments the glass had to be ground while the closed segments were silvered in order to obtain good reflecting surfaces. The grinding necessitated the glass being of considerable thickness and this obviously entailed a very marked decrease in intensity at the instant of alternation. The next disk was constructed by silvering four small thin similar plates of glass and mounting them on a metal disk in such a way that they formed equiangular closed and open sectors. It was discovered, however, that it was not possible to mount these in such a way as to have them exactly in the same plane. The succeeding disk was constructed simply of polished aluminum metal by filing out the rectangular slots which served as the open sectors while the polished metal was judged to be a satisfactory reflector for the closed sectors. The use of this disk brought about considerable improvement but the click was still present to some degree. It was, therefore, concluded at this stage of the work that with the mechanical facilities available it was not possible to put this theoretical sound principle into practice.

In the above arrangement, due to the production of a continuous current, the conventional resistance, — capacity

coupling shown in Fig. 15, was used so that only changes in the photoelectric current produced a change in the drop of potential across the resistance R which was in turn impressed on the grid of the valve. The latter was maintained at the proper average potential by means of the blocking condenser C and the grid leak resistance γ . The value of this potential is merely such that the operating range is maintained on the linear portion of the grid-potential, plate-current characteristic of the valve, (Fig. 13).

Since this double arm compensating method did not work properly it was thought well to revert back to the first arrangement and put on a second stage of amplification and determine to what extent this would increase its sensitivity. The coupling used for the second stage was the non-inductive type (Fig. 16) first suggested by H. D. Arnold.⁽¹⁶⁾ The advantages of this coupling are that it eliminates the necessity of using a transformer or a condenser and it serves equally well for a wide range of frequencies. The grid bias battery E_g and the resistance R_1 , serve the purpose of maintaining the grid of the second valve at the proper average potential.

The set of readings obtained by rotating the Nicol N_1 so that the hum just became audible is recorded in Table IV. The terms "left" and "right" refer to the direction in which the Nicol was rotated.

Table IV

Left	Right
300° 39'	302° 29'
300° 44'	301° 51'
300° 47'	302° 12'
300° 47'	302° 29'
300° 39'	302° 23'
300° 30'	302° 12'
300° 50'	302° 08'
300° 22'	302° 00'
300° 33'	302° 08'
300° 49'	302° 20'

The mean square error of these readings is $\pm 3' 23''$. Comparing these results with those obtained in Table III when only one stage of amplification was employed, it is seen that the second stage of amplification decreases the mean square error of the readings by $1' 25''$. Thus, theoretically by increasing the number of stages of amplification sufficiently a fair degree of accuracy could be obtained. In practice, however, this is not feasible for two reasons. In the first place, the point at which the hum becomes audible is shifted, with each additional stage of amplification, to regions of lower intensity of light and consequently the distinctness of the initial hum is not greatly improved. Secondly, there is a definite limit to the number of stages of amplification which can be usefully employed.

This is due to the transfer of energy which takes place from the plate circuit back to the grid circuit of the same thermionic tube, and also from any part of one stage of amplification to any part of a preceding stage. This phenomenon is known as "feed-back". If the energy fed back to the grid circuit is equal to or greater than the energy loss in that circuit due to its resistance, a signal voltage introduced into the grid circuit will set up sustained oscillations in the tube. It then ceases to act as an amplifier.

The tendency of the tube to oscillate may be reduced by several different methods. First, the elimination of couplings through which energy can be transferred from the output to the input circuits. These couplings may be inductive, such as the coupling between coils; capacitive, as the coupling between nearby wires, coils, or other parts that are at different voltages; and finally, the coupling may be through a resistance common to the different stages, such as that of a common "B" battery supply. The most effective method of eliminating the inductive and capacitive couplings is to use metal shields between the parts in question. The action of these shields will be explained later. Resistance feed-backs, on the other hand, may be largely overcome by using separate batteries for each stage of amplification though such an arrangement is highly

impracticable due to the space and expense involved.

A second method of diminishing the tendency toward oscillation is to introduce a second feed-back, the effect of which is opposite to that which unavoidably takes place. This method is used in all bridge circuits.

A third method is to reduce the power in the plate circuit below the point at which there is sufficient excess energy to cause oscillation. This, however, diminishes the amplification obtained per stage.

It is not possible to eliminate all feed-back and as it naturally increases with each additional stage of amplification, it definitely sets a limit to the number of useful stages of amplification. The sensitivity obtainable with the single optical path arrangement and employing the optimum number of stages of amplification was not tested since the accuracy of this method is not independent of fluctuations of either the source of illumination or the photoelectric cell, and then it is not applicable to the measurement of absorption as well as the rotation of the plane of polarization.

The suggestion was then made that probably the principle used in modern visual polarimeters, explained earlier, could be applied with advantage to a "null audible" photoelectric polarimeter as it might be termed. This was accomplished by using the much desired double optical path

(Fig. 12) by decreasing the intensity in one arm to correspond to the quantity ΔI and having it periodically interrupted and its intensity varied until the effect it produced on the hum in the receivers just became inaudible. The set of readings given in Table V below, however, shows that this arrangement is very inaccurate, the reason being that the ear is not nearly as sensitive as the eye in this respect; that is, the value of Weber's constant $\left(\frac{\Delta I}{I}\right)$ is much larger for audition than it is for vision.⁽¹⁷⁾

Table V

43° 45'	44° 10'
44° 50'	44° 45'
44° 45'	43° 00'
43° 10'	45° 15'
42° 30'	43° 50'

The next change that was made in this double compensating method was in the means adopted to determine when the two beams were of equal intensity. The telephone receivers were replaced by a transformer, a rectifying valve, and a micro-ammeter as shown in Fig. 16. The primary of the transformer was connected into the plate circuit of the second amplifying valve (UX-112A) while the rectifying valve (UX-201 A used as a diode) and the micro-ammeter were connected in series with the secondary of the transformer. Thus, when the two beams were of equal intensity, there was a certain

minimum steady deflection registered on the micro-ammeter. This deflection was the result of the change in intensity at the time of alternation but since the duration of this change is very short it does not produce a large deflection. If, on the other hand, the equality of the beams was upset by rotating slowly the Nicol N_1 the current in the secondary of the transformer increased very rapidly as indicated by the micro-ammeter reading. It was found that a rotation of $3^\circ 30'$ caused the current to increase by 100 microamperes. Thus by rotating the Nicol until a certain desired deflection was produced, it was possible to obtain readings on the vernier of the Nicol that checked very closely as is shown in Table VI below.

Table VI

352° 00'	358° 10'
351° 59'	358° 10'
351° 57'	358° 09'
351° 57'	358° 10'
351° 57'	358° 10'
351° 59'	358° 09'
351° 58'	358° 08'
351° 59'	358° 10'
351° 58'	358° 11'
351° 58'	358° 10'

The mean square error of these readings is $\pm 18''$

which is almost as low as an experienced operator can obtain with the best type of visual polarimeter under the most suitable conditions. ⁽⁹⁾ The accuracy of this instrument can, however, be improved upon. For example, the vernier attachment on the Nicol permitted readings only to the nearest minute to be taken. With this arrangement, it is evident, from Table VI, that the mechanical limit of accuracy has been attained but this limit would be greatly lowered if a micro-meter adjustment were provided.

In taking the above readings, Nicol N₁ was adjusted until a deflection of 50 microamperes was obtained. The terms "left" and "right" refer to the side of the minimum deflection (32 microamperes) to which the Nicol was set. The adjustment was not made for this minimum deflection because the micro-ammeter employed was not sufficiently sensitive since one scale division represented two microamperes. This procedure, however, does not make the instrument completely independent of all fluctuations, namely those of the source, photoelectric cell and batteries, although these enter only on a greatly reduced scale. The steady deflection was considered to be too large to be solely the result of a change in intensity at the instant of alternation of the two beams; it seemed to be at least partly due to the inequality in the intensity of the reflected beam from the closed sectors of the disk. Another disk was therefore constructed with

particular care as follows. A circular plate of brass was obtained of such thickness that it could be "turned out" in the lathe. A perfectly smooth face was thus secured after it had been polished. The closed sectors were then silver-chromium plated so that their reflecting powers were both good and uniform. The use of this disk was found to decrease the minimum deflection to such an extent that another stage of amplification could be added which in turn increased the sensitivity sufficiently to allow the point of minimum deflection to be taken as the position of balance.

The actual arrangement of the electrical parts of the instrument is shown in fig. 17. A resistance-capacity coupling was employed between the different stages of amplification. As has been previously mentioned under "amplification" the value of the coupling resistances is of great importance, particularly in case of the first stage, i.e., resistances R and Y in fig. 17, since the incoming signal is generally weak. The most satisfactory values for each of these resistances R and Y were found to be approximately 100 megohms; lower values were found to decrease the sensitivity while those having higher values introduced instability due to accumulation of electrons on the grid. To obtain these resistors, different types were tested but those obtained by ruling india ink on paper were found most satisfactory both because they varied the least with time and they could

factors, since, when they impinge upon it, their energies are dissipated by being transformed into eddy currents. The effects that they have on the apparatus within the box is thus greatly diminished. One will see that the resistance of the conducting material of the box should be as low as possible in order that the eddy currents be readily formed within its mass. Copper is consequently the best to use, but aluminum and brass are also good. Iron and steel, on the other hand, should never be used for two reasons; first, their resistances are relatively high compared with the metals mentioned above, and secondly, magnetic effects are introduced since they have magnetic fields of their own. It is impossible to build a perfect shield because even the best conductors have some resistance and therefore do not absorb all the energy of the incident disturbance. In order to be effective, a shield must be as complete as possible, and all joints in it must be soldered so as to ensure good electrical contact between its parts. Furthermore, the shield should be grounded so that whatever forces are induced in it are neutralized or eliminated by conducting them to earth.

The shielding of the first stage is most important since a disturbance introduced here is subsequently amplified to the same degree as the desired incoming signal. The cell and the first tube were, therefore, doubly shielded by

placing them within a small secondary box.

In order to test the operation of the instrument as described above, a few absorption measurements were taken. The absorption tube was first of all placed empty in the position occupied by tube T_1 (fig. 12) and the balance point was secured by rotating N_1 until the minimum deflection was registered on the micro-ammeter. The tube was then successively filled with known concentrations of the solution in question and the adjustment for balance repeated in each case. A curve showing the relation between the concentration of the solution and the resulting absorption was thus secured. Two such curves are shown in figure 18. These curves were obtained with an ordinary incandescent electric bulb used as the source of illumination since a monochromatic source was not available. This accounts for the shape of the curves since with white light, it is known that, " as the concentration increases, the character of the "change is such that the nature of the transmitted radiation tends to become constant and capable of further transmission without absorption." (18) This is what the curves clearly indicate.

It is to be noted that with this instrument the equivalent of a monochromatic source of illumination can be realized by using a "monochromatic" photoelectric cell and a source emitting white light. Such a cell, although a very common type was not available.

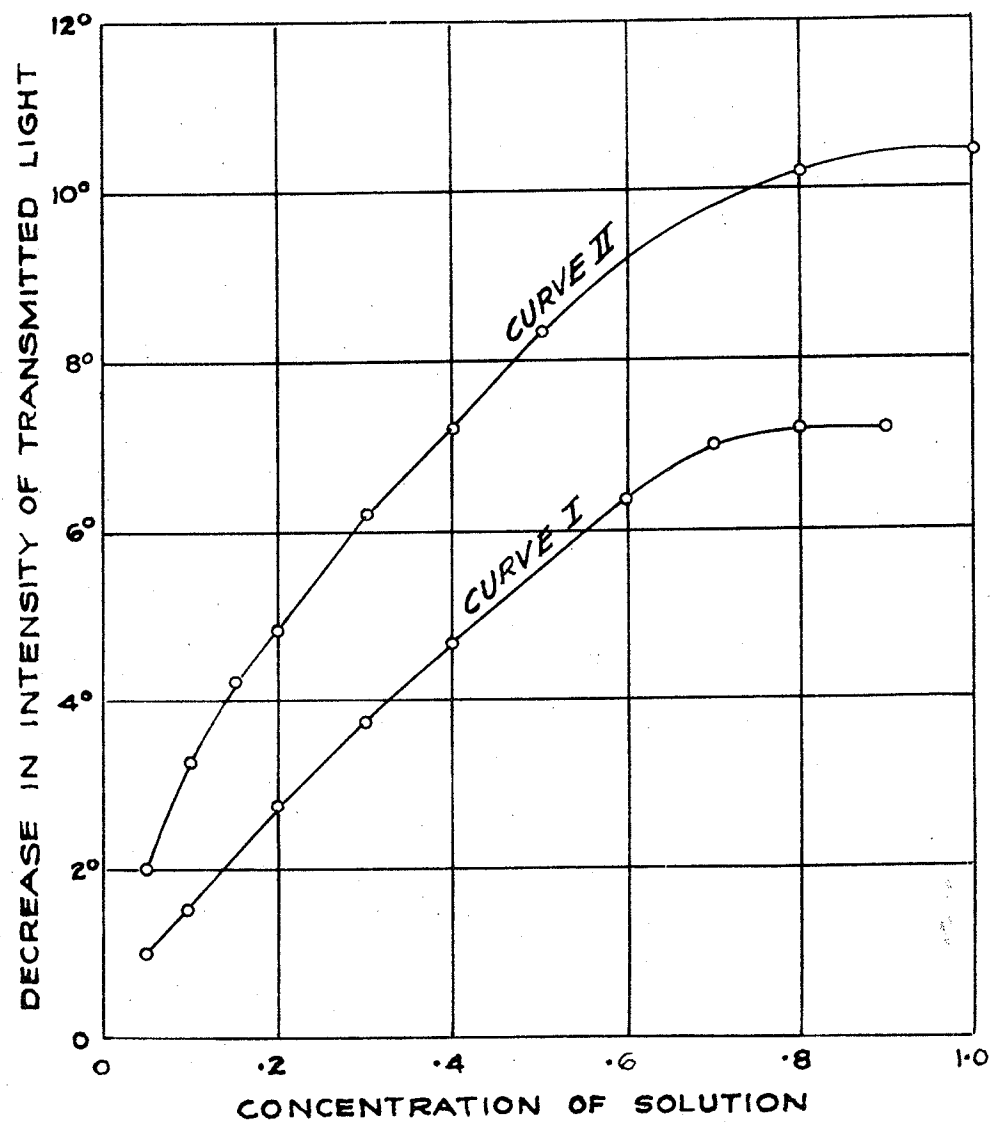


FIGURE 18

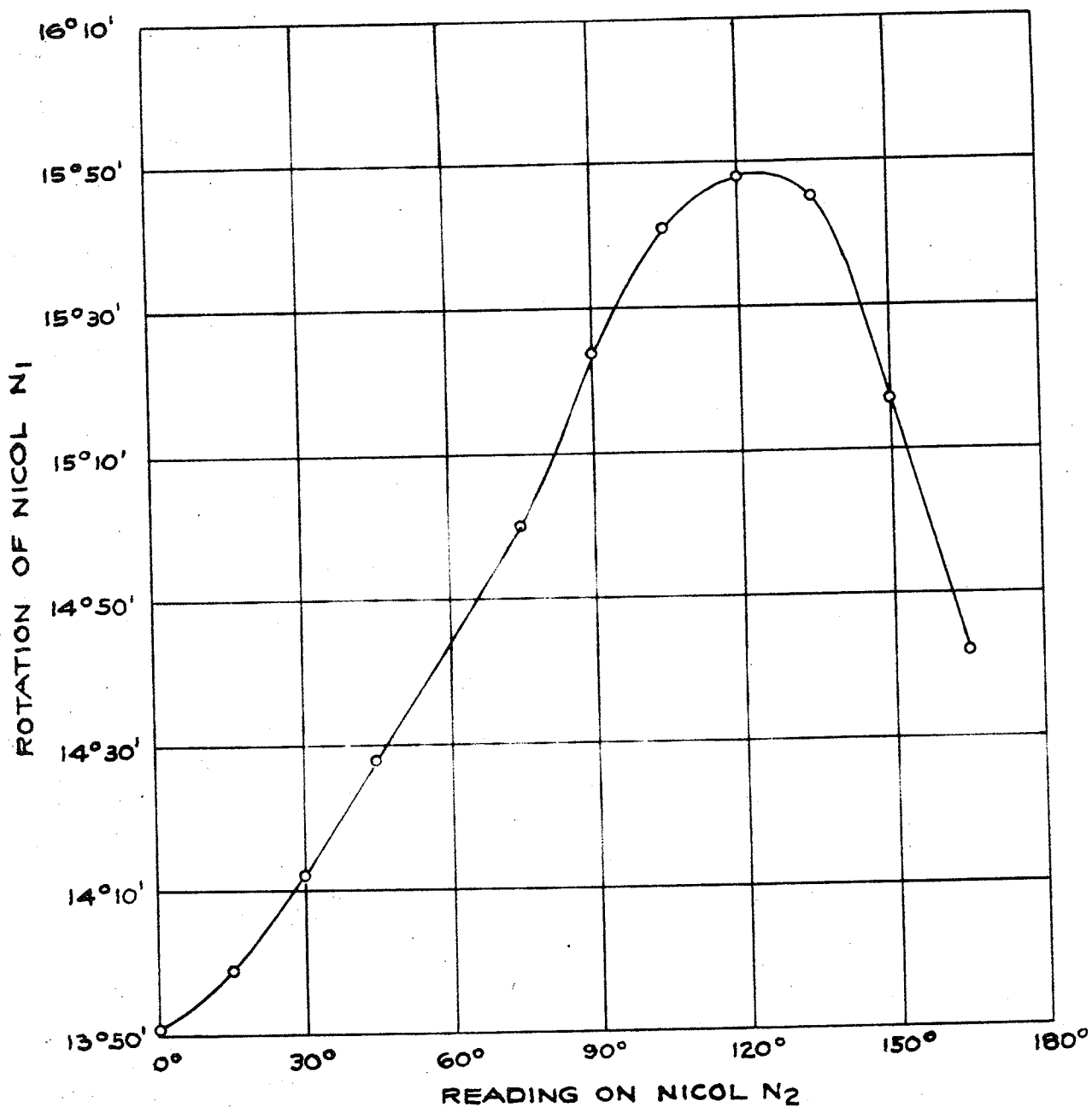


FIGURE 19

Another noteworthy fact is that extraneous illumination of steady or slowly fluctuating intensity does not affect the instrument since the basis of its operation is that it responds only to rapid fluctuations of light intensities. This salient feature concerning the instrument eliminates the necessity of protecting it from extraneous light.

In obtaining readings with this instrument, Nicol N_1 , and not N_2 , should always be rotated when making the adjustment for balance because altering the latter would change the orientation of the plane of incidence on the photoelectric cell. This in turn alters the sensitivity of the cell as is clearly illustrated by the curve (fig.19) which was obtained by rotating N_2 through successive angles of 15 degrees and in each case noting the angle through which N_1 had to be rotated in order to restore the fixed reference reading on the micro-ammeter. This change in sensitivity was anticipated since it is a known fact that the photoelectric emission from the metals of which the threshold lies in the visible region of the spectrum is characterized by a relatively enormous protuberance imposed at one part on the general steady fall with increasing wave length. The presence and magnitude of this protuberance has been found to depend intimately on the mode of incidence of the light; for example, in the case of plane polarized light, it appears only if the electric vector has a component perpendicular to the surface. Thus, even though the surface of the

cathode is matt, it is to be expected that the emission varies somewhat with the mode of incidence of plane polarized light, as was experimentally verified.

This procedure, however, of rotating Nicol N_1 , introduces a slight error because the illumination from all sources is polarized to some extent. In case of incandescent sources, as employed above, this effect is inappreciable.

It is to be noted that this method of measurement is properly termed a "null" method since the reading on the recording instrument at or near zero is made to correspond to the standard with which the comparison is made. One of the advantages of this method is increased sensitivity of the kind that results from a suppressed zero in a direct reading instrument, i.e., it permits a more sensitive recording instrument to be used. There is also a gain in the kind of sensitivity that results from regularity, i.e., the effect of the variation of the source, photoelectric cell, and batteries is eliminated; this gain arises as a result of the rapidity with which the substitution is made between the standard and the one to be measured. Furthermore, there is a gain in accuracy which is best illustrated by the following analogy. The common bridge method of measuring resistances is more accurate than the direct reading method because the law that the resistances in corresponding arms

are proportional is more nearly true than the law that the resistance is inversely proportional to the deflection. Similarly in this instrument the compensating magnitude acts in the very same way as the magnitude to be measured and consequently the law that the two beams are equal when the deflection is a minimum is more nearly true than the law that the deflection is proportional to the intensity of the beam of light incident on the photoelectric cell which is the basis of the "standard" substitution method.

This instrument could easily be adapted to take measurements in the ultra-violet region of the spectrum by using quartz prisms and lenses, a special type of Nicols or their equivalent, and a photoelectric cell that had its maximum sensitivity in the region that was being investigated. The frequency of the alternation of the two beams would also have to be made so high that the arrangement was independent of fluctuations of even the most variable ultra-violet sources, such as open arcs.

The superiority of this null photoelectric polarimeter then lies in its accuracy, simplicity and rapidity of taking readings, and in the possibility of adapting it to obtain measurements in the ultra-violet region of the spectrum.

In conclusion, I wish to express my thanks to Dr. P. A.

Macdonald, Assistant Professor of Physics, for the suggestion of this problem and for his generous advice; also to Dr. Frank Allen, Director of the Department of Physics of the University of Manitoba, for the facilities of the Research Laboratory which were placed at my disposal.

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