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Title THE DEVELOPMENT OF A PHOTOELECTRIC CELL SUITABLE FOR
STUDENT USE IN THE DETERMINATION OF PLANCK'S CONSTANT

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The design and construction of a photoelectric cell having a small spherical photosensitive surface placed at the geometric center of a spherical collector electrode is described. With the concentric arrangement of the electrodes a greater photoelectric current can be measured under retarding potentials than with cells of the usual commercial design. This permits finding the stopping potential with greater accuracy.

A sensitive surface is produced by condensation of potassium vapor on the central emitter electrode which is kept cold by running water while the entire cell is heated to 350°C in an electric oven. This method avoids the possibility of getting potassium on the outer collector electrode which would be affected by scattered light and produce an inverse photoelectric current complicating the determination of the stopping potential.

The potassium is sensitized by a trace of sulphur vapor and then by a normal discharge through hydrogen in the cell, using the collector and an auxilliary electrode as terminals. A sensitivity of approximately five micro-amperes per lumen of white light was obtained.

A detailed description of the pumping system and accessory equipment is given as well as a step-by-step account of the construction, assembling, out-gassing and sensitization of the photoelectric cell.

THE DEVELOPMENT OF A PHOTOELECTRIC
CELL SUITABLE FOR STUDENT USE
IN THE DETERMINATION OF
PLANCK'S CONSTANT

by

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TABLE OF CONTENTS

	Page
INTRODUCTION -----	1
THE PHOTOELECTRIC CELL IN GENERAL -----	5
DETERMINATION OF h BY USE OF THE VACUUM PHOTOELECTRIC CELL -----	7
THE NEED FOR A BETTER CELL -----	9
THE NEW DESIGN -----	11
CONSTRUCTION OF THE CELL -----	13
THE PUMP AND ACCESSORIES -----	15
OUTGASSING AND EVACUATION -----	19
CONCLUSION -----	23
Figure 1	
Figure 2	
Figure 3	
Plate 1	
Plate 2	
BIBLIOGRAPHY	

THE DEVELOPMENT OF A PHOTOELECTRIC
CELL SUITABLE FOR STUDENT USE
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INTRODUCTION

The purpose of this thesis is to describe the design and construction of a photoelectric cell suitable for use by undergraduate students in determining Planck's constant with reasonable accuracy through the application of Einstein's theoretical equation for the photoelectric effect. The cell has not been designed with the intention of correcting present accepted values of the constant, but to make available a procedure for constructing a sensitive vacuum photoelectric cell free from leakage and inverse currents inherent in cells of commercial design when used for determining Planck's constant.

Max Planck first used the constant, h , in a formula in 1900 in an effort to express the energy distribution of the radiation from a black-body. Having found the correct formula his interpretation of it led to the quantum theory of radiation, wholly inconsistent with the classical electromagnetic theory. In 1905 Einstein's photoelectric equation, involving the energy of the radiation quantum, further strengthened the quantum theory and gave the only explanation of the photoelectric effect.

The photoelectric effect is the emission of electrons from atoms or a piece of metal by direct absorption of

radiant energy. Lawrence⁽⁵⁾ and Beams showed that electrons are emitted within 10^{-9} seconds of the time radiation strikes a photoelectrically active surface. From this fact it is clear that radiant energy must travel in concentrated packets, or quanta, since no appreciable time seems to be required for the electron to gather energy from radiation. The quantum of radiant energy is called a photon. The energy of each photon is constant and is equal in ergs to h times the frequency, f . In the photoelectric effect the entire energy of the photon is believed to be received by a single electron which enables that electron to escape provided the work of escaping does not require more energy than was received. The least energy of escape from a metal surface expressed in electronvolts is called the work function, ϕ , of that surface and is characteristic of any pure metal but is greatly affected by contamination of the surface. ϕ can be thought of as an hypothetical barrier-potential against which an electron must do work, ϕe ergs, to escape (e is the charge of the electron in e.s.u.).

The Einstein photoelectric equation relates the energy, hf , of the photon with 0 and the kinetic energy of the released electron, $1/2 mv^2$;

$$hf - \phi e = 1/2 mv^2 \quad (1)$$

where f is the frequency of the radiation and h is Planck's

constants.

The first successful theoretical model of the hydrogen atom, introduced by Niels Bohr in 1913, required that the angular momentum of the electron in its orbital motion be limited in values to integral multiples of $h/2\pi$. Bohr stated that there were only certain discrete energy values permissible for the hydrogen atom as determined by the electron's orbital momentum, and that changes in this energy content were due to absorption or emission of quanta of values hf_H where f_H represents frequencies found in the hydrogen spectrum.

Sommerfeld in 1916 showed that each degree of freedom of any harmonic oscillator is separately quantized as indicated by the equation,

$$\oint p \, dq = nh \tag{2}$$

where p is the generalized momentum and q is the generalized displacement.

It is now known that these principles with modifications and restrictions apply to all atomic and molecular systems.

The constant, h , has the dimensions of energy times time or momentum times distance and is called the quantum of action.

It has long been known that it was of extreme importance to all quantum theory calculations to have an accu-

rate value for h . Any formula relating h to other constants or functions separately determinable, can serve as a means of evaluating h . There are seven index methods for determining h which were mentioned by Birge⁽¹⁾ in 1929 in a discussion of probable values of the general physical constants.

The errors in the probable values of h as determined by the seven different methods differ little. This is due largely to the error in the value of the charge of the electron which enters into five of the calculations. Birge gives as the weighted mean of these seven values,

$$h = 6.547 \pm .008 \times 10^{-27} \text{ erg-sec.} \quad (3)$$

Birge pointed out the inconsistency existing between the values of atomic constants. When any one of the constants is calculated by more than one relationship from values of other constants there usually appears a discrepancy between values in excess of the estimated probable error.

In 1939 Dunnington⁽³⁾ and DuMond⁽²⁾ seemed to agree that the discrepancy probably lay in an incorrect value for the ratio h/e , and their suggestion was that new attempts be made to determine the ratio h/e by methods other than that employing X-rays. The accuracy of the X-ray method has been developed to a high degree.

THE PHOTOELECTRIC CELL IN GENERAL

The photoelectric cell is a device in which radiant energy is absorbed and partially transformed into electrical energy, or influences the flow of an electrical current. Photoelectric cells take various forms depending on the photosensitive material used and the requirements for utilizing the properties of this material. They may be divided into three classes.

1. Photoconductive cells are typified by the common selenium cell. The intensity of incident radiation controls the conductivity of the cell.

2. Photovoltaic cells are typified by the cuprous oxide cell in which a difference of potential, a function of the intensity of the incident radiation, is set up across the photosensitive boundary between the oxide and the pure metal.

3. Vacuum photoelectric cells have two electrodes sealed in an evacuated envelope which may contain gas at low pressures. One electrode is made of, or coated with, the photosensitive material upon which the light falls and from which electrons are released. This is the emitter electrode. The other is made of any metal and is called the collector electrode since it collects electrons which reach it.

Regardless of the type of cell, its action is believed

to be due to the photoelectric effect.

DETERMINATION OF h BY USE OF THE VACUUM PHOTOELECTRIC CELL

In determining h by the photoelectric method the emitter electrode of a vacuum photoelectric cell is irradiated with monochromatic light of variable frequency. A potential difference is applied between the emitter and collector electrodes making the collector negative and consequently establishing an electric field opposing the flow of electrons to the collector.

For each frequency used the retarding potential is adjusted until the most energetic electrons are just prevented from reaching the collector. Their energy will then be $V_s e$, where V_s is the so-called stopping potential. Stopping potentials are found more precisely by plotting the square root of the photoelectric current against the retarding potential as first done by Lukirsky⁽⁶⁾ and Prilezaev. This gives a straight line making the intersection with the axis easy to locate, thus giving more accurate values of the stopping potential. The values of stopping potential are plotted against their respective frequencies and a straight line is drawn through the points.

By substituting $V_s e$ for $1/2 mv^2$ in the photoelectric equation (1), it is rewritten,

$$V_s e = hf - \phi e. \quad (4)$$

Dividing by e to get an expression for V_s ,

$$V_g = h/e f - \phi \quad (5)$$

it is seen that the curve for this equation is a straight line whose slope is h/e . The value of this slope can be taken from the empirical plot of V_g against f .

The measured value of V_g , however, is not the actual potential of the field acting on the electron. There is a field set up by the contact potential difference between the emitter and collector metals which is the difference between their work-functions.

The presence of this contact potential difference, V_c , in the circuit necessitates changing equation (5) to

$$V_g + V_c = h/e f - \phi. \quad (6)$$

The values of V_c and ϕ need not be known for determining h since they do not change the slope of the curve.

THE NEED FOR A BETTER CELL

Since the photoelectric cell is, at best, an inefficient device for converting radiant energy into electrical energy, the usual commercial type photoelectric cell contains a relatively large emitter electrode possessing the photoelectrically active surface. The collector is usually restricted in size to allow a free view of the emitter.

If the usual commercial type of cell is used for determining h , and the retarding potential is applied to the collector, only those electrons emitted with velocities initially in the direction of the small collector have any chance of reaching it, and when the retarding potential is increased the paths of many electrons are curved to the extent of missing the collector while the electrons may still possess sufficient energy to reach it. As a result the photoelectric current to be measured is extremely feeble. Inverse currents caused by leakage and the photoelectric effect due to scattered light on the collector electrode, make it impossible to get accurate values for the stopping potentials.

Most of the commercial cells that are sensitive to visible light have an alkali metal condensed on the emitter surface. Surfaces of alkali metals have longer wave-length thresholds than those of any other pure metals. The wave-length threshold for a surface is the longest wave-length

light may have and still be capable of ejecting an electron from that surface. The threshold wave-length is λ in $\phi_e = hc/\lambda$. When the alkali metal is condensed on the emitter surface it is done in a vacuum and no attempt is made to prevent the metal from condensing on the collector electrode. A monatomic film is all that is necessary to sensitize the collector and permit scattered light to produce an inverse photoelectric current.

If the emitter electrode is not concentric with the collector electrode, the stopping potential is made still more indefinite by the fact that the retarding potential acts on varying components of the electron's velocity and makes it necessary to restrict illumination to a small spot on the sensitive surface.

THE NEW DESIGN

The new cell was designed to eliminate most of the undesirable characteristics which have been discussed in connection with commercial cells.

The collecting electrode consists of a silver coating on the inside of the spherical cell envelope. The photosensitive surface is restricted to a small rounded electrode located at the geometric center of the collecting electrode. A window is provided in the collecting electrode for the entrance of light to the active surface.

The application of a retarding potential to this cell produces a field which is everywhere practically radial to the collecting electrode and the source of electrons. If the active surface could be restricted to an infinitesimal point electrode at the center of the cell, each electron, upon ejection, regardless of direction, would be traveling in exact opposition to the field and would be prevented from reaching the collector only by the full magnitude of the stopping potential. This would result in a much greater current and a steeper curve for the plot of current against retarding potential. The restriction of the active surface to a hemisphere 8 mm in diameter is sufficient approach to the point source to give the desired sharp determination of the stopping potential.

The fact that the area of active surface is necessari-

ly restricted makes it desirable to use a surface with a high sensitivity. This was prepared according to a method outlined by Olpin⁽⁷⁾. The sensitive surface is of potassium treated with sulphur and sensitized by making it the negative electrode in a momentary discharge in hydrogen. The exact nature of the final surface is not understood.

This surface has a sensitivity of, roughly, six microamperes per lumen of white light from a tungsten filament lamp. The sensitivity⁽⁷⁾ is a maximum for a wave-length of approximately 4000 Angstroms which is well above the threshold wave-length of 2610 Angstroms for the silver collector electrode⁽⁴⁾. The threshold wave-length for the sensitized potassium surface is approximately 6000 Angstroms. This makes it possible to avoid inverse currents due to the photoelectric effect at the collector surface by using wave-lengths longer than 2610 Angstroms.

A method for restricting the potassium entirely to the central emitter electrode is described on page 20. The fact that this can be done is one of the principal advantages of this design. The slightest trace of potassium must be kept from the silver collector if its threshold wave-length is to remain near 2610 Angstroms. The short wave-length limit of transmissibility of pyrex glass is approximately 2900 Angstroms, making it impossible for the photoelectric effect to occur at the collector electrode.

CONSTRUCTION OF THE CELL

A one-liter round-bottomed pyrex flask was used for the envelope. The extended window shown in figure 1 at A was made by cutting a one-inch disk of sheet-pyrex and sealing it to the end of a piece of tubing. The tubing was drawn down, cut, and sealed to the center of the bottom of the flask. The constriction of the window extension was for the purpose of making the necessary opening in the collector electrode as small as practical and thereby preventing undue distortion of the electric field.

The connecting lead to the silver collector electrode was made by sealing two tungsten wires of 0.040 inch diameter into the cell envelope as shown at C. To insure connection to the silver coating the two wires were allowed to extend inwards about 5 cm. They were flattened at the ends and bent so as to spring gently against the collector electrode on the flask wall.

Two tubes were sealed into the side of the flask near the neck, with constrictions to facilitate seal-offs. These tubes were for the introduction of sulphur and potassium as explained later.

The support for the central emitter electrode was a pyrex tube containing a tungsten connecting lead near the rounded end as shown at G and H.

Before sealing in the central tube, the tip of this

tube and the inner surface of the flask were silvered. The silvering solutions were prepared according to the Brashear formula. The central electrode was carefully cleaned in the usual manner and silvered on its rounded tip end by dipping it into the silvering solution and stirring gently while the silver was depositing. Excess silver deposited more than two centimeters from the end of the tube was easily rubbed off while the coating was still wet. After careful cleaning the flask was silvered by simply mixing the solutions in a separate container and then pouring the mixture immediately into the cell. A cork prevented the solution from silvering the window. The flask was carefully held with the open neck up except for repeated tilting to insure silvering the inside of the stem containing the leads for the collector electrode. The edge of the silver coat was trimmed while still wet to a smooth line by a tool made of a piece of heavy wire wrapped with cotton.

The central electrode support was next sealed in place in the stem of the flask, thus completing the basic mechanical operations of construction.

THE PUMP AND ACCESSORIES

The cell was mounted on the pumping stand with the stem downward and the seal-off tube joined to the pump manifold.

The pumping system consisted of a two-stage oil diffusion system and a rotary fore-pump. The diffusion units were constructed entirely of metal. A mercury cut-off was used between the pump and the cell. To protect the system from mercury vapor a layer of pump oil was laid over the mercury in the cut-off. After each admission of air to the system this oil had to be gently heated to outgas it.

Between the cut-off and the cell there was a trap which was cooled by a mixture of solid carbon dioxide and acetone during the final evacuation and seal-off, for the purpose of reducing the amount of oil vapor diffusing back into the cell from the pumps.

A spiral of tungsten was used as an electrode in the manifold next to the cell. This was primarily for permitting a discharge through hydrogen gas, using as the other electrode the collecting electrode of the cell. This electrode came in very handy, however, as a test electrode in determining the preliminary behavior of the pumping system on many occasions.

A palladium tube was sealed to a piece of soft glass which, in turn, was joined to the pumping system through a

waxed tapered joint. The palladium was used as an entrance for hydrogen gas during sensitization of the active surface. Heating the palladium tube with a Bunsen flame makes it sufficiently permeable to hydrogen so that unburned hydrogen in the flame diffuses through to the extent of a few hundredths of a millimeter of pressure.

The pressure in the system was determined by an ionization gauge. Figure 2 shows the connections for the gauge. Several types of vacuum tubes were used, including types 45, 200 and 276A, as well as two built in the laboratory. In all cases except with the type 276A tube, the filaments burned out after short use. The filaments were not used at excessive temperatures but seemed, rather, to burn out because of ion bombardment during outgassing.

It is necessary to outgas the elements of the tube at a pressure below 10^{-3} mm before a steady reliable reading of the plate current micro-ammeter can be obtained. Until this is done the plate current is always too large for proper operation and may increase to harmful values. The outgassing is accomplished by connecting the grid and plate of the ionization gauge to a potential of around 2000 volts from a transformer, and increasing the filament temperature until the plate is heated to a cherry-red color. This should not be attempted until a spark-tester applied to the electrode in the manifold indicates that the pressure in the system is too low to maintain a gaseous discharge. Gas

is often evolved so rapidly during outgassing that a gaseous discharge of destructive intensity can be initiated before the pumps remove the gas. To prevent this it is best to use a transformer with sufficient magnetic leakage to limit the current output to that required for outgassing. The outgassing can also be done slowly or in short intervals to give the pumps time to carry away the gas. These precautions are not necessary when small tubes are used but they are essential with the type 276A transmitter tube, which gave the best life and was easiest to outgas.

Each ionization gauge should be calibrated. Since it was never necessary to know the pressure in the system with any exactness, all gauges used were considered to behave like the type 45, the calibration for which was worked out in the University of California Physics laboratory at Berkeley. The pressure in mm of mercury equals $1/20 \frac{I_p}{I_q}$, where I_p is the plate current in amperes and I_q is the grid current, or filament emission current, in amperes. The gauge was used principally for determining the extent of outgassing in the cell and to make sure that the highest vacuum possible was attained at the time of seal-off.

About 2 g of sulphur were placed in the last of a series of two bulbs 3 cm in diameter on the end of a 30 cm tube which was sealed to the tubulure provided on the cell, as shown at C in figure 3. A series of three bulbs for the purification and introduction of potassium was attached to

the cell as shown at B.

The potassium in the form of a five gram ball was placed inside a press shown at A. The press, placed in a vice and compressed, extruded potassium wire through the side hole. It was caught in a bulb with a long thin neck. The potassium was melted and heated until kerosene fumes ceased to leave the bulb. After the potassium had solidified in the bulb it was inverted with the long neck extending down into the first of the bulbs in the series attached to the cell as shown at B. The potassium was melted and allowed to run down into the bulb, after which the stem was sealed off at (a), finally closing the vacuum system and making it ready for evacuation.

OUTGASSING AND EVACUATION

Before a permanent high vacuum can be reached in the evacuation of any cell, it is necessary to heat the entire cell to as high a temperature as the envelope will stand and to maintain that temperature during pumping until the glass and all metal parts are sufficiently outgassed.

For heating the photoelectric cell an oven was built consisting of 1/2 inch asbestos boards forming a rectangular box completely surrounding it. The heating elements of the furnace consisted of four closely wound coils of number 20 nichrome wire hung on the inside walls of the box and connected in parallel. A rheostat controlled the electric current through the heating elements.

The temperature inside the oven was held at approximately 500° C, as indicated by a hard glass thermometer, for 24 hours of continuous pumping before it was possible to hold a vacuum of 10^{-6} mm of pressure with the cut-off closed. It is believed that the prolonged baking was required because of excessive outgassing of the silver collecting electrode.

During the outgassing of the cell the sulphur and potassium were also outgassed and purified for introduction into the cell. The sulphur was simply melted and gently distilled into the adjoining bulb.

The potassium was melted and slowly distilled over into bulb number 2. The first bulb was sealed off at (b). The

potassium was then distilled into bulb number 3 and back again to bulb number 2, then again to number 3 when bulb number 2 was sealed off at (c). Both bulbs numbers 2 and 3 were carefully flamed and outgassed before potassium was distilled into them. The connecting tube leading to the cell was flamed also.

It was now necessary to cool the cell to room temperature in order to start a stream of cold water flowing through the central electrode support tube. The water was squirted up against the central electrode and allowed to run down the neck of the cell which extended through the bottom of the oven. This kept the central support tube cool as the oven was reheated to a temperature of about 300° C. Potassium was distilled into the cell and condensed on the central electrode, the rest of the cell being hot enough to drive all the potassium to the center. About one gram of potassium was allowed to enter the cell, then the oven was cooled and removed.

The method just described for condensing potassium on the emitter electrode and, at the same time, completely preventing condensation on the collector electrode proved to be very effective, as will be shown later.

From this point on, it was necessary to test the photoelectric sensitivity of the cell from time to time to determine the required amounts of the remaining constituents and treatments.

A 100 watt clear lamp was mounted 3 1/2 cm from the cell window. The cell was connected in series with a one megohm resistor, a 16 1/2 volt battery and a Leeds Northrup wall-type galvanometer shunted with 300 ohms and having an effective sensitivity of 3×10^{-8} amperes per mm of deflection. The collecting electrode was made positive. The plain potassium surface gave a photoelectric current of 0.2 microamperes.

Unfortunately, an excessive amount of sulphur was allowed to enter the first cell constructed and ruin the silver collector electrode.

The following step-by-step procedure was that employed in sensitizing the second cell. This treatment was that used by Olpin already mentioned.

The sulphur bulb was warmed slightly and the galvanometer watched. When the slightest trace of S had entered the cell the current rose to 3.5 microamperes. Upon attempting to add an additional trace of S it was found that the current dropped to 2.5 microamperes.

Hydrogen was now introduced by heating the palladium tube with a Bunsen flame until the pressure in the system rose to about 0.1 mm. The current increased to 3.0, dropped to 2.4 in a few seconds and then slowly increased to 2.5 microamperes.

A discharge was produced for 0.2 seconds between the collector electrode as positive terminal and the manifold

electrode as negative terminal. No high voltage was connected to the sensitive surface. The discharge caused the photoelectric current to drop to 2.4 microamperes. Another discharge lasting 1.0 second caused the current to drop to 2.4 microamperes.

The hydrogen was now pumped out during which the current gradually increased in 20 minutes time to 4.1 microamperes.

The pumping was continued and the tube leading to the sulphur bulb was sealed off. After this the current had reached 4.4 microamperes. The potassium tube was sealed off next and the current read 5.0 microamperes where it seemed to be fairly constant.

The cell was sealed off the pumps. No change in the current took place.

To test for leakage current the battery was reversed, making the collector electrode negative, and the light turned off. No current was detected, indicating adequate insulation.

While the battery was reversed the light was turned on, still, no current could be detected, indicating that no electrons were leaving the collector surface, and proving that its wave-length threshold was lower than the shortest wave-length of light entering the cell.

CONCLUSION

Since photoelectric currents as high as five microamperes were obtained with the arrangement described, it is seen that there is sufficient sensitivity to make it possible to use the new photoelectric cell with monochromatic light sources and galvanometers ordinarily available in the average laboratory.

The tests made on the completed photoelectric cell show that the described design effectively eliminates those characteristics inherent in commercial designs, which are undesirable when determining h . The tests also indicate that the procedure outlined for construction and sensitization of the cell is entirely satisfactory.

The fact that no current was detected when the collector electrode was made negative with 16.5 volts indicates that the method employed for concentrating the potassium on the central electrode was thoroughly successful. If the silver collector had been poorly outgassed or contaminated with no more than a monatomic layer of potassium, its wave-length threshold could easily have been extended into the range of wave-lengths transmitted through glass, and a photoelectric current would have been detected.

Considerable detail in regard to manipulative technique has been included in this thesis. Such information is hard to find and should be helpful to anyone engaged in

a similar project.

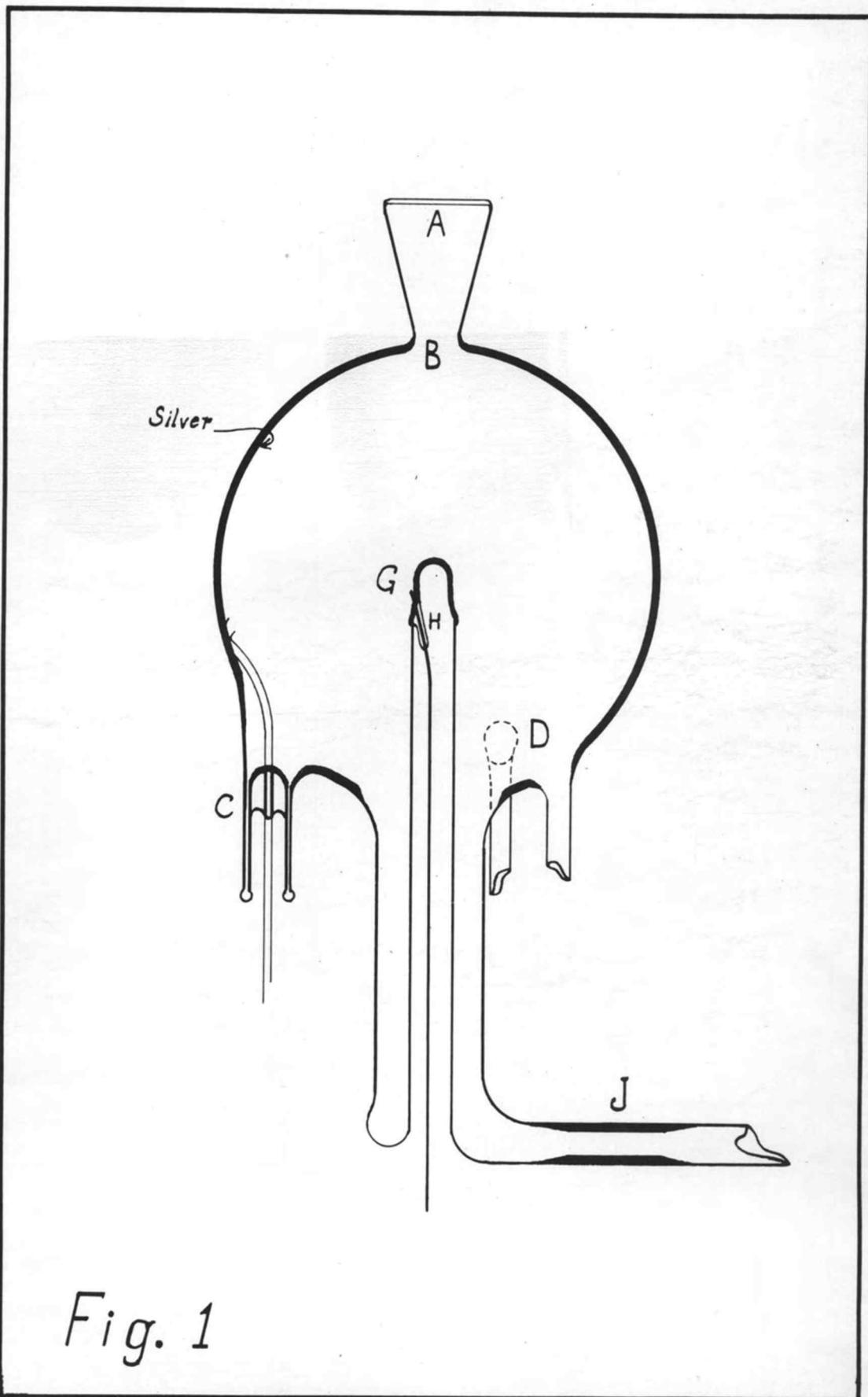


Fig. 1

*Ionization
Gauge*

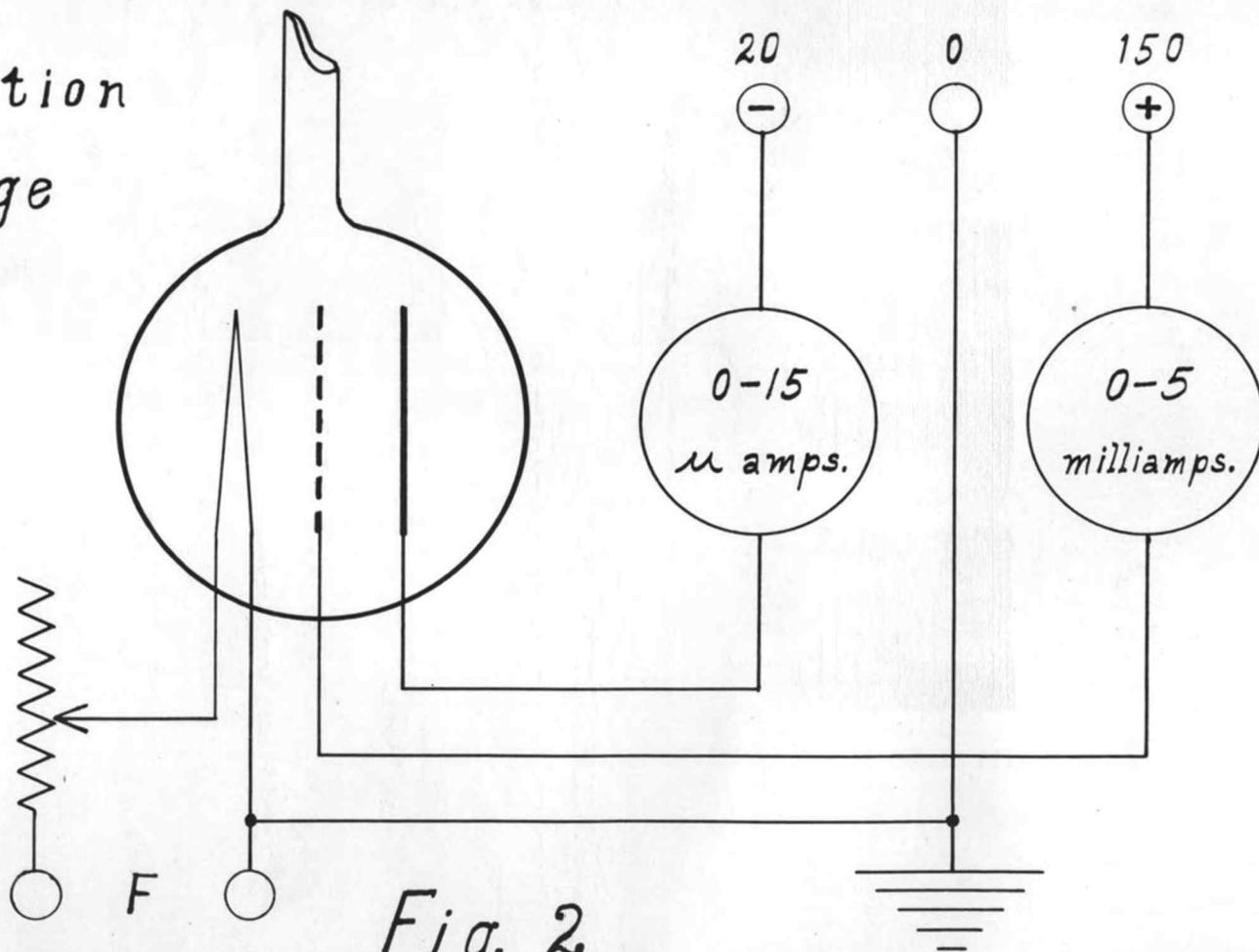


Fig. 2

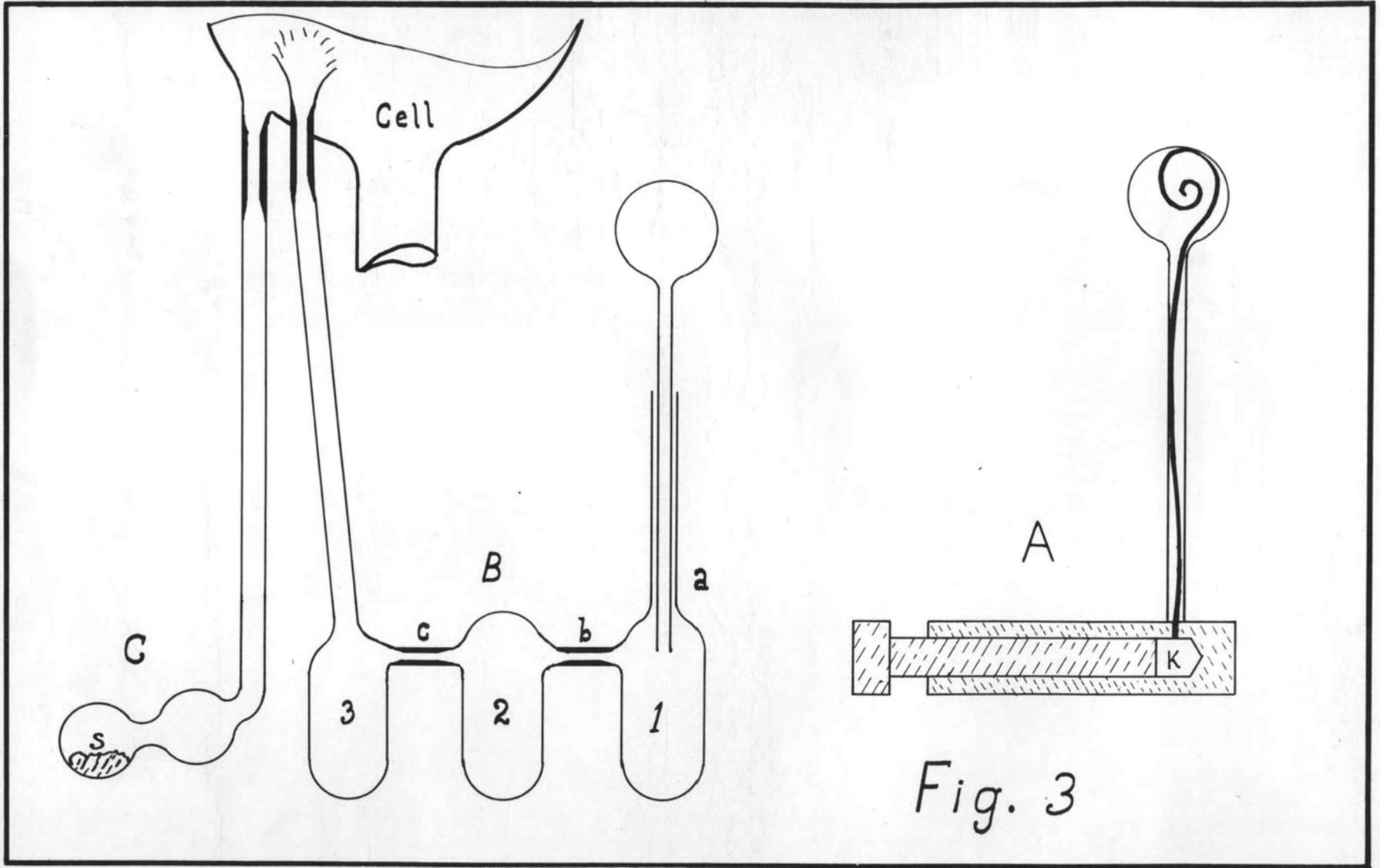
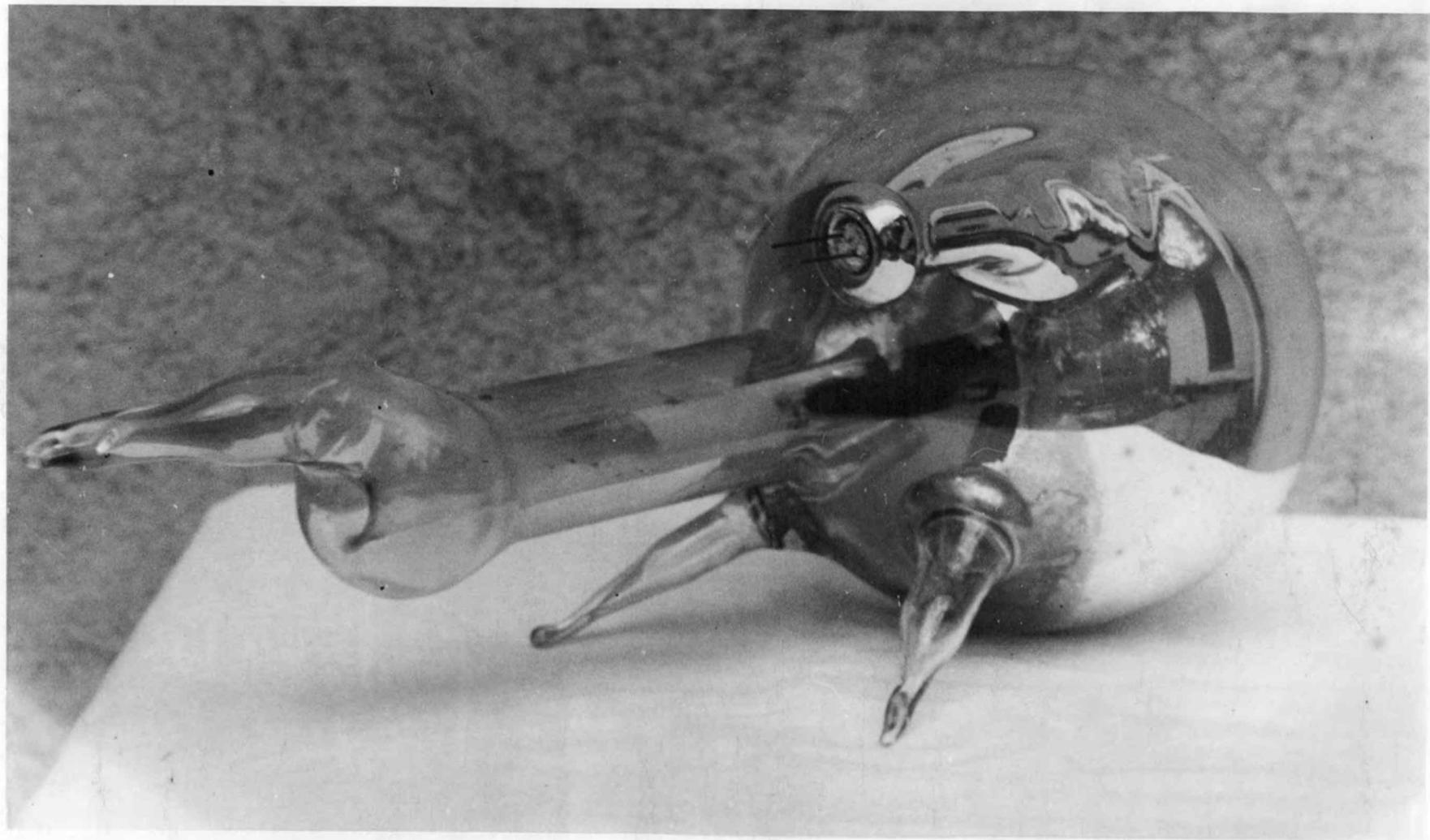


Fig. 3



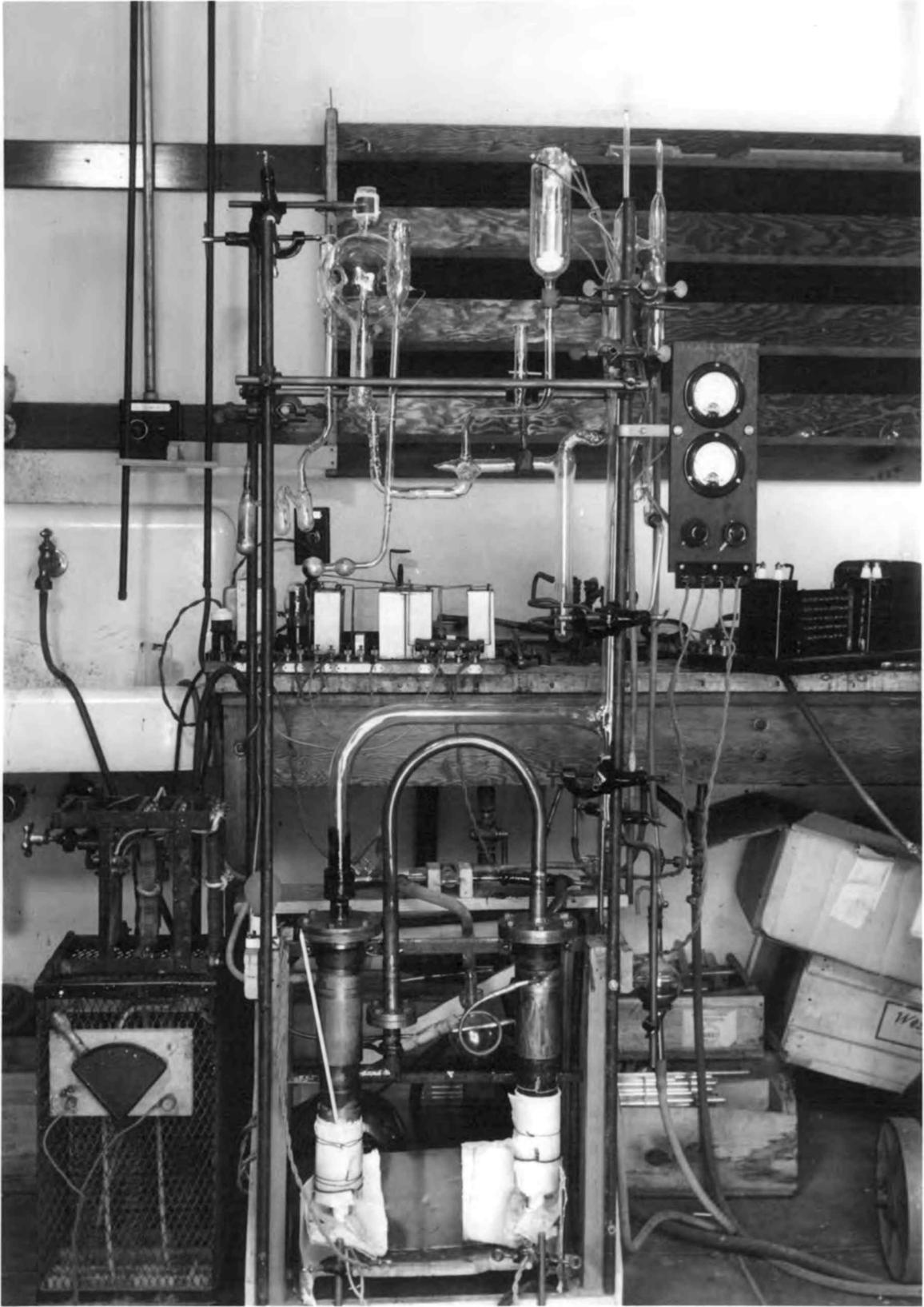


Plate 2

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