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Development of a Two Channel Counter for Measurement of Faraday Rotations

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DEVELOPMENT OF A TWO CHANNEL COUNTER FOR MEASUREMENT OF FARADAY ROTATIONS

by

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Donald R. Flach

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CHAPTER I

INTRODUCTION

The rotation of the plane of polarization of plane polarized light when it passes through a substance in a direction parallel to an applied magnetic field is known as the Faraday effect and was discovered by Michael Faraday in 1845.[1] It was found by experimentation that the amount of rotation of the plane of polarization was represented by the equation:

$$\theta = VHl \cos A$$

where H = magnetic field in gauss, l = sample path length in centimeters, A is the angle between the magnetic field and the direction of the light, and V is a proportionality constant known as Verdet's constant.[2] Actually, V is a function of wavelength and temperature. For most measurements, however, wavelength and temperature are held constant and hence V remains constant. The rotation varies greatly with changes in wavelength and only slightly with changes in temperature. The sense of the rotation is defined as that which rotates in the sense of a right handed screw advancing in the direction of the field.[3]

The Faraday effect can be detected with the arrangement shown in Figure 1. With the magnetic field turned off, no light will be transmitted by the analyzer. When the magnetic field is turned on, the plane of polarization is rotated, and the analyzer will transmit light. The analyzer is then rotated until no light is transmitted, and the angle between the original analyzer setting and the new one is the amount of rotation of the plane of polarization.

Figure 2 shows an experimental arrangement for studying the variation of Faraday rotation with wavelength. This method of measuring the rotation incorporates the use of photographic plates as detection devices. The advantages of using photographic plates as detection devices are:

(1) permanent record of the spectrum,

(2) integration over a period of time of the light from a source of varying intensity,

(3) high sensitivity.

The disadvantages are:

(1) a darkroom is needed,

(2) a microphotometer is needed,

(3) long lengths of time needed to obtain data.

The use of photomultiplier tubes, when coupled with direct reading equipment, offers a fast, accurate and sensitive method of measurement. Photomultiplier tubes used in this way are comparable in sensitivity with photographic plates, for any spectral line which can be photographed in two hours may be measured directly with a photomultiplier measuring unit which incorporates high sensitivity with speed and convenience of measurement.

ARRANGEMENT FOR DETECTING THE FARADAY EFFECT

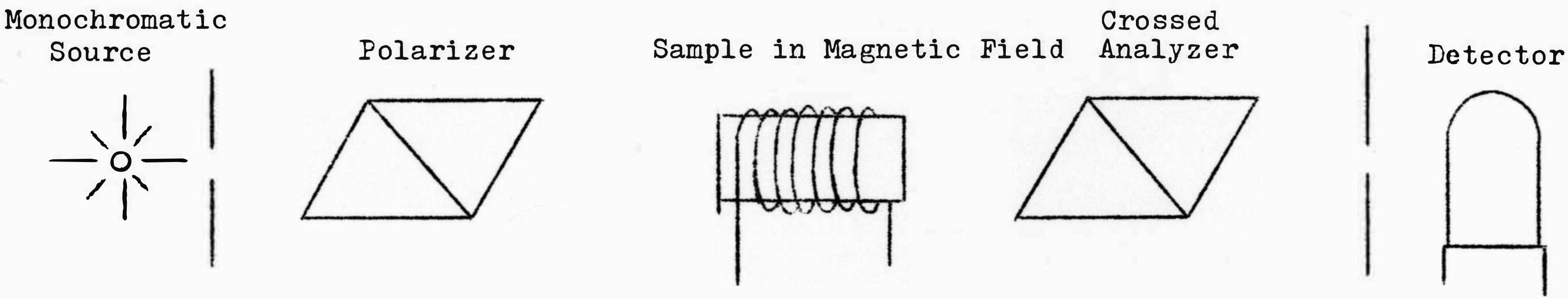


Figure 1

EXPERIMENTAL ARRANGEMENT FOR STUDYING THE FARADAY EFFECT

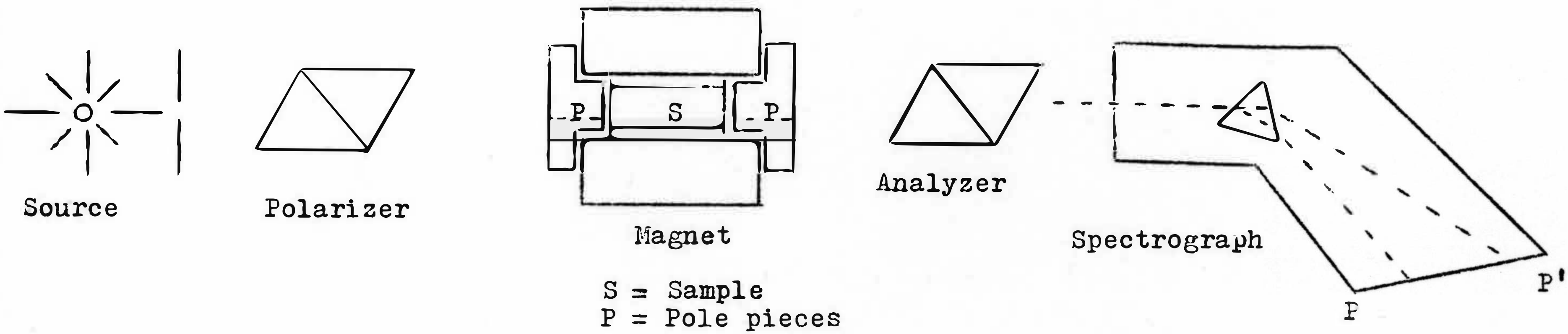


Figure 2

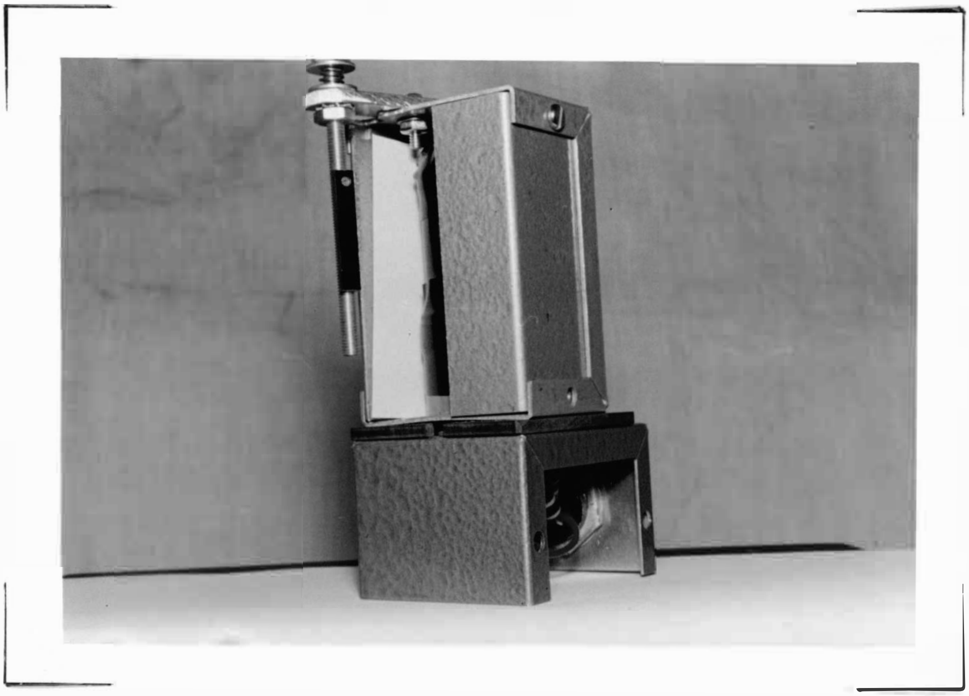
CHAPTER II

ELECTRONIC CIRCUITRY

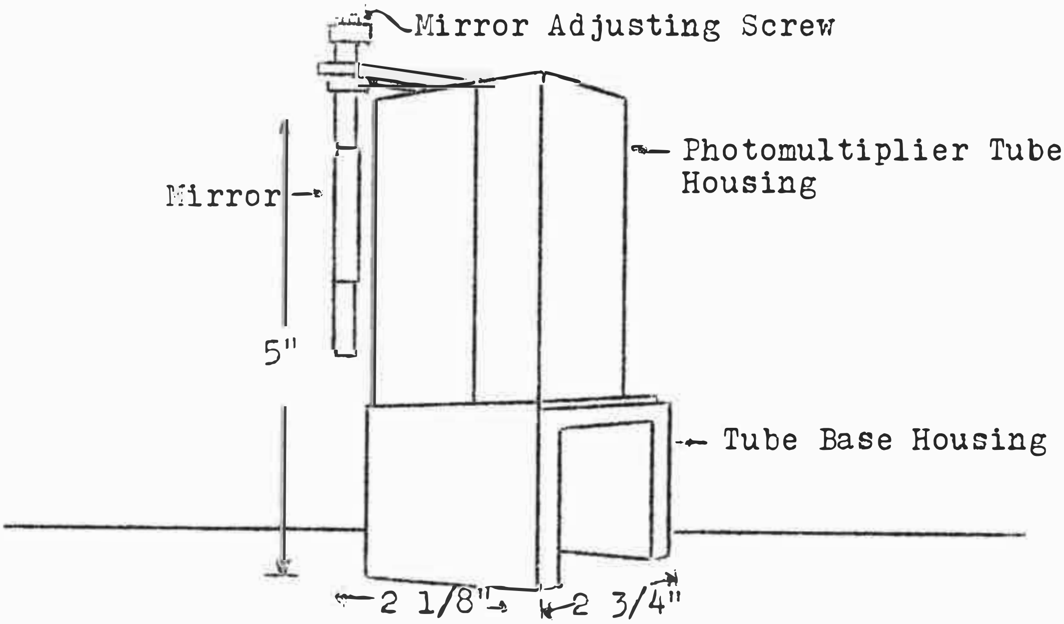
Three types of photomultiplier tubes were used in this study. These are: the 931-A, the 1P21 and the 1P28, all produced by RCA. The 931-A is designed for use in the visible region and has a current amplification of approximately 950,000 as used in this circuitry. It has the disadvantage of relatively high dark current when compared with the 1P21 or 1P28. Dark current is defined as the current that flows from the tube when no light is falling on the cathode. The 1P21 and 1P28, which are constructed similar to the 931-A, are designed for measuring low light levels. The 1P21 features high current amplification and low dark current relative to the 931-A. It is designed for use in the visible range and has a current amplification of ~1,200,000 as used in this circuitry. The 1P28 has a special envelope of ultraviolet transmitting glass having a cut-off near 2000 Å. It has lower dark current than either the 931-A or the 1P21. Current amplification of the 1P21 as used in this equipment is ~1,050,000.

Figure 3 shows a mirror arrangement used to deflect the light entering the focal plane of the spectrograph into a slit on the photomultiplier tube. A narrow slit is made on the glass surface of the tube with electrician's

MIRROR ARRANGEMENT USED TO DEFLECT LIGHT INTO SLIT ON PHOTOMULTIPLIER TUBE



(a) Photograph



(b) Block Diagram

Figure 3

tape to sharpen the spectral range of the light striking the photomultiplier cathode. The entire remaining surface of the tube is covered with two layers of tape to shut out spurious light. It would also be possible to mount an adjustable slit between the mirror and the surface of the photomultiplier tube which would accomplish the same purpose. The mirrors are constructed from stainless steel so they will reflect both ultraviolet and visible light with negligible absorption. Dimensions of the mirrors are approximately $1\frac{1}{4}$" long and 3/16" wide. They are mounted on a 10-32 type machine bolt by means of 0090 type brass screws 3/16" long. Details of the mounting may be seen in Figure 3. A spring and a slit cut in the top of the machine bolt allow adjustment of the mirror with a screwdriver and hold it in position after adjustment.

Use of the mirrors is not necessary, as the photomultiplier tubes may be used without it. However, use of the mirrors permits better control of the light coming in and more accurate determination of the wavelength the tube is set at.

All three of the above photomultiplier tubes need a stable, high voltage power supply for satisfactory operation. The power supply constructed for use with the above photomultiplier tubes utilizes the voltage drop across a series of VR tubes for a stable, high

CIRCUIT DIAGRAM OF POWER SUPPLY FOR PHOTOMULTIPLIER TUBES

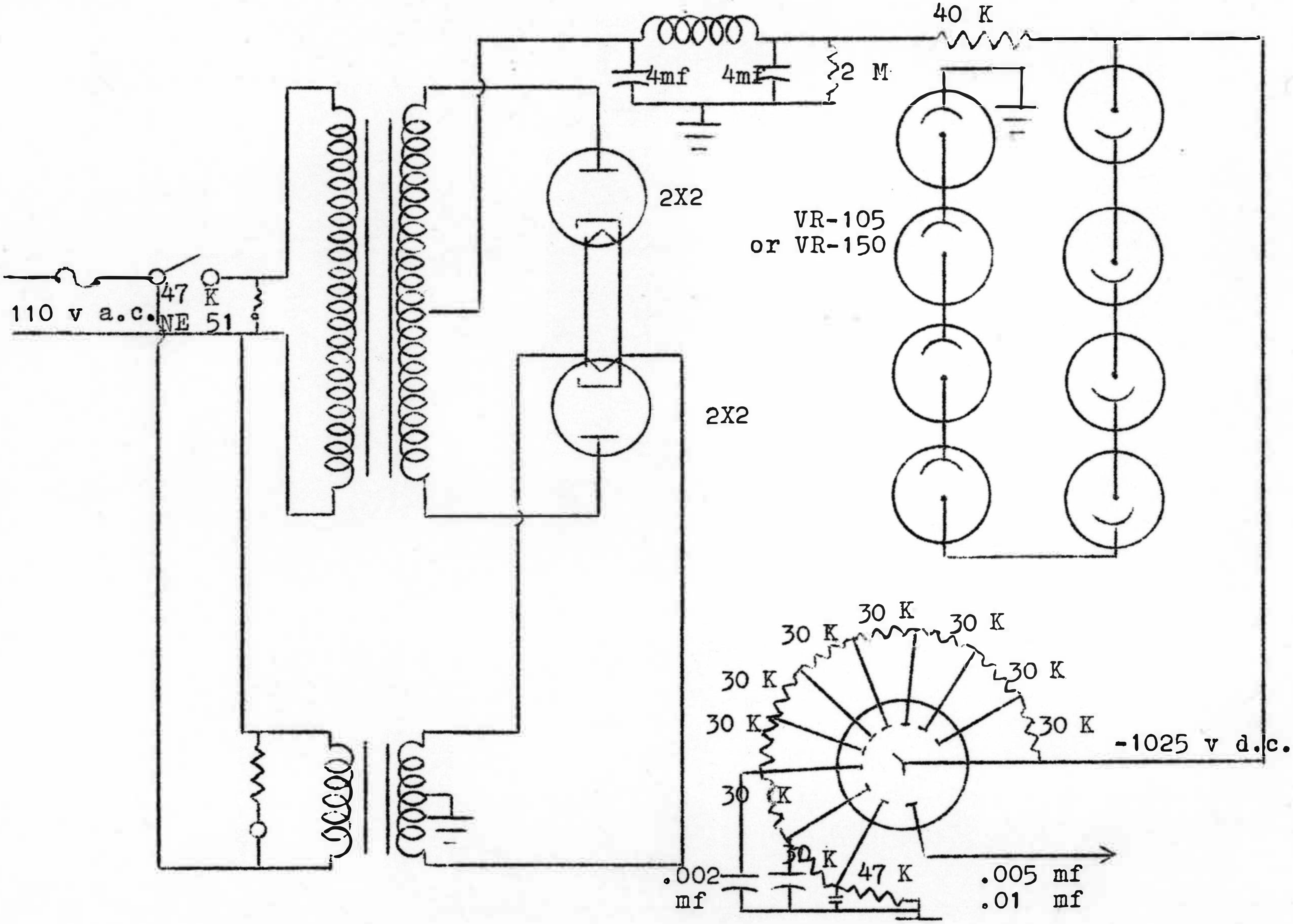


Figure 4

voltage power supply. A series of five VR-150's and three VR-105's produces a measured minus 1025 d.c. power supply. A voltage divider mounted on the base of the photomultiplier tube socket provides for a potential difference of 90 to 100 volts per stage (per dynode) and a 150 to 170 volt potential difference at the anode. Figure 4 is a circuit diagram of the power supply and the voltage divider mounted on the base of the photomultiplier tube. Physical connection to the voltage divider is made through the output circuitry connected to the photomultiplier tube.

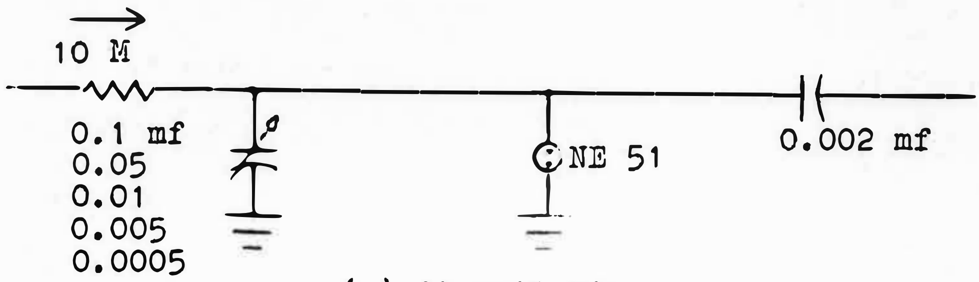
The instabilities in light intensities of all the gaseous light sources create fluctuating currents in the detectors and make measurements difficult with galvanometers, sensitive microammeters, and vacuum tube voltmeters. Therefore, a circuit was constructed which will integrate the fluctuating current over the measurement time. Figure 5 (a) shows the arrangement used to integrate the output current. This is the input circuit in Figure 6. A capacitor is placed in parallel with a neon bulb which has a breakdown potential of 60-70 volts. When the potential of the neon bulb is below 60 volts, the neon bulb acts as an open circuit. When the potential reaches 60-70 volts, the gas in the neon bulb breaks down and the bulb conducts, partially discharging the capacitor. This produces a pulse which will pass through the remaining circuitry and operate a mechanical register. The purpose of the various capacitor settings is to control the rate of breakdown of the neon bulb and prevent jamming of the counting circuit by the high pulse rate.

Figure 5 (b) shows the electron flow and polarities before breakdown of the neon bulb. Initially a flow of electrons builds up a minus charge on the circuit side of the capacitor and a plus charge on the ground side. Thus, before breakdown, the input circuit exerts a slight negative potential on the grid of the 12AU7. Figure 5 (c) shows the electron flow and polarities after the capacitor has been charged to 60-70 volts by the current flowing from the photomultiplier tube. The current flow from the photomultiplier tube is ignored during the breakdown of the neon bulb. When the extinguishing potential of the neon bulb is reached, which is 15-20 volts below the breakdown potential, the bulb ceases to conduct and the circuit reverts back to the description given in Figure 5 (b). This circuit produces a positive potential for a brief period on the grid of the 12AU7 tube when the neon bulb breaks down.

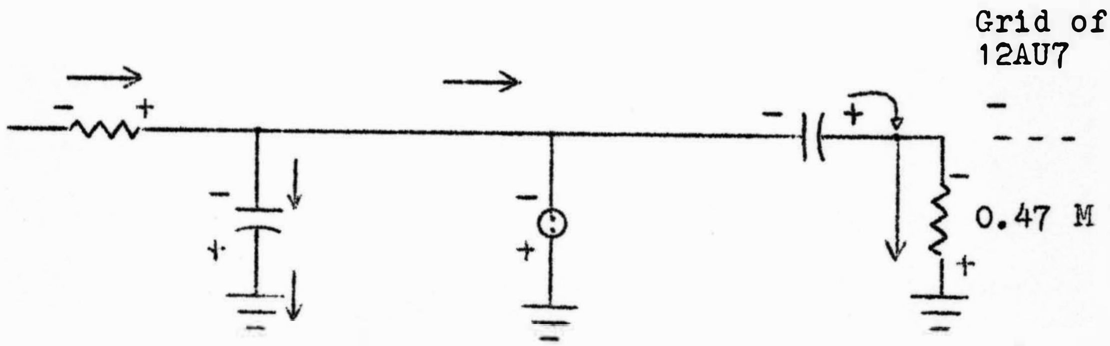
Since the positive output pulse from the neon-bulb-capacitor circuit is very narrow, it is necessary to lengthen and change its shape so it will be able to trigger a tube which will operate a mechanical register. A plate coupled monostable multivibrator is used to lengthen and change the pulse shape. The lengthened

CURRENT INTEGRATOR DIAGRAMS

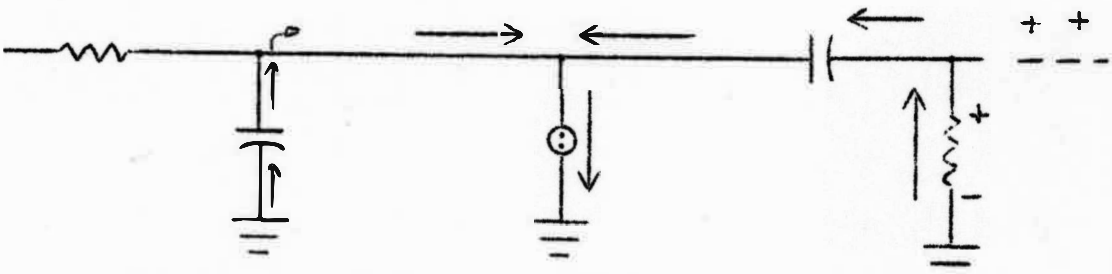
From Photomultiplier Tube



(a) Circuit Diagram



(b) Electron Flow and Polarities Before Breakdown



(c) Electron Flow and Polarities during Breakdown of the Neon Bulb

Figure 5

pulse from the monostable multivibrator then goes to a driver tube which operates the mechanical register. Figure 6 is a circuit diagram of the integrating circuit. (See Appendix I for a description of the monostable multivibrator and mechanical register driver circuit). Figures 7 and 8 are two views of the power supply and two scalers set up with the photomultiplier tubes for a two-channel method of measurements.

An alternate type of trigger circuit was tried. Figure 9 is a circuit diagram. It was hoped that a vacuum tube trigger circuit would start to discharge the capacitor at a lower voltage than the neon bulb, and that the breakdown voltage where the vacuum tube would start to conduct would be more stable than that of the neon bulb.

The alternate trigger circuit shown in Figure 9 works on the principle that V1 is initially in a non-conducting condition. When the charge on capacitor C_1 reaches a large enough potential, the tube starts to conduct, discharging the capacitor. The coupling to tube V2 decreases the current through that tube, which decreases the grid potential on V1. This action further discharges the capacitor. When the capacitor is discharged, the potential on the grid of V1 rises back to its cutoff value and the tube ceases to conduct. This circuit failed to work in a satisfactory manner due, it is believed, to tube V1 leaking away the charge on the capacitor even when it was supposed to be cut off.

INTEGRATING CIRCUIT

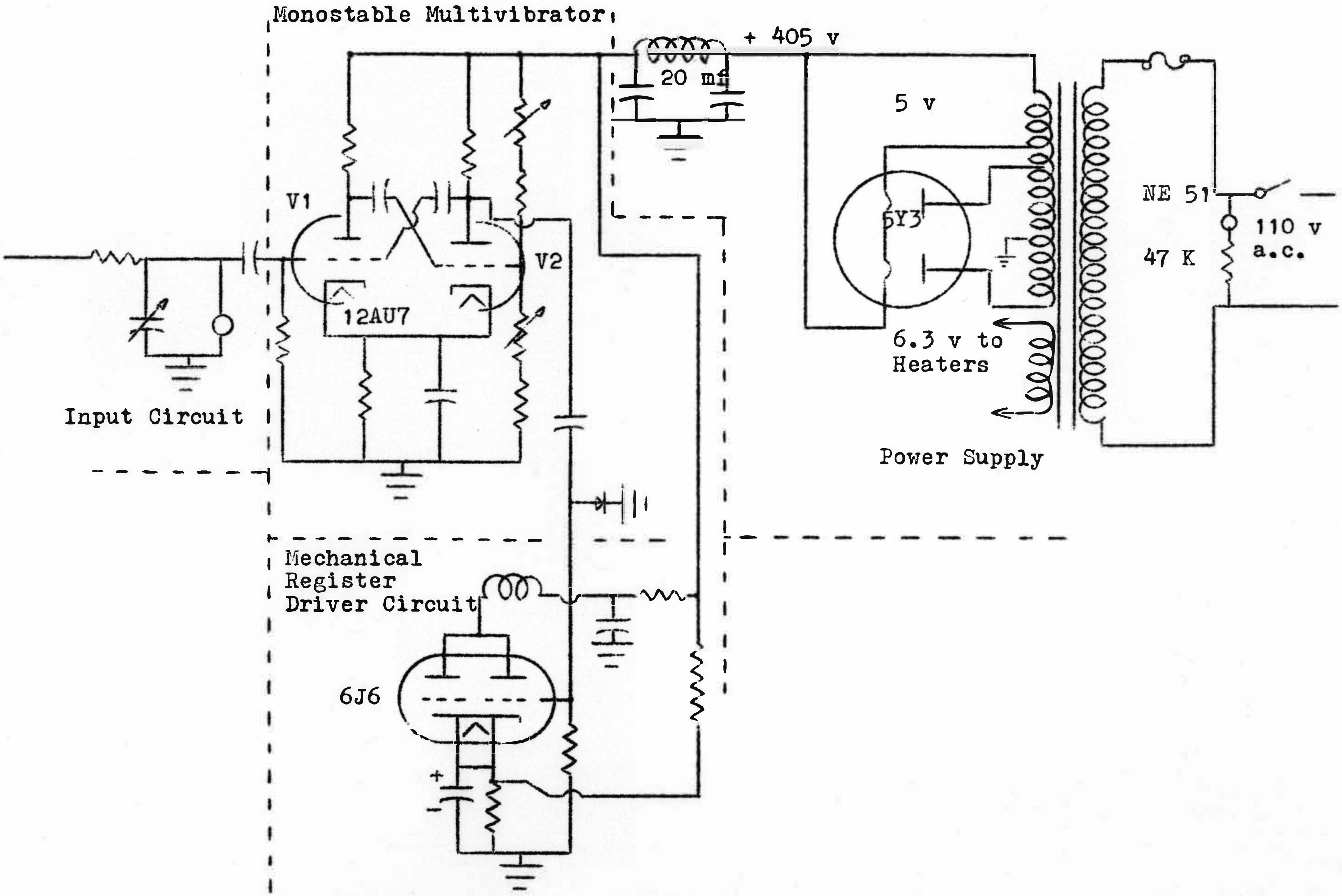


Figure 6

FARADAY EFFECT APPARATUS

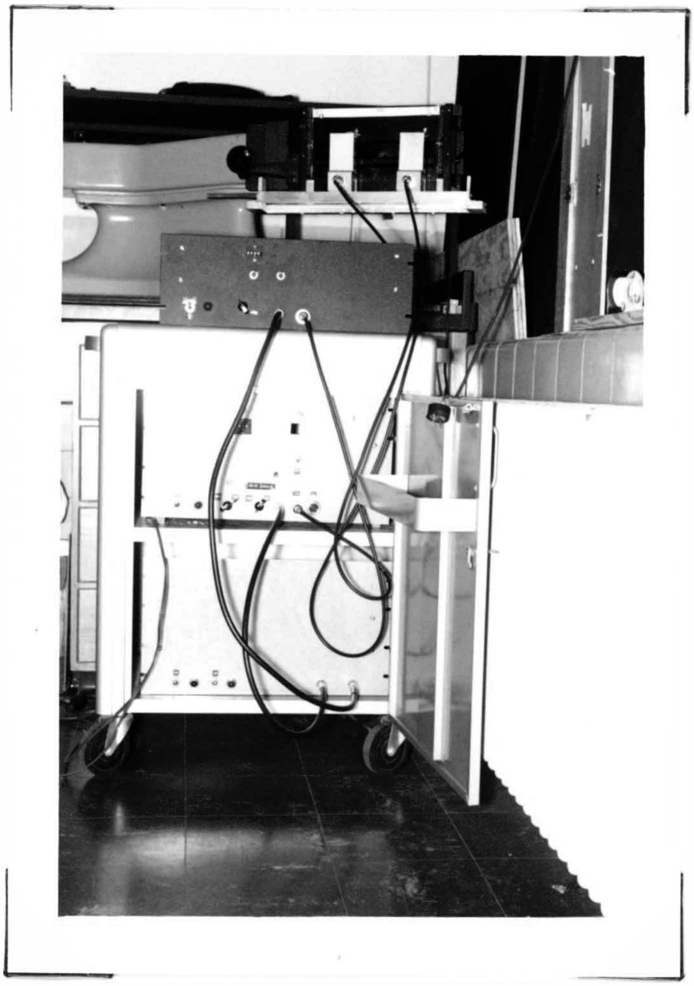


Figure 7

This photograph shows the equipment set in operating position. In actual operation, a black cloth covered the two photomultiplier tubes. From top to bottom the pieces of equipment shown in the photograph are: two photomultiplier tubes mounted on the focal plane of the spectrograph; one scalar on the movable cart; a second scalar in the top of the movable cart; and the power supply in the bottom of the cart.

PHOTOMULTIPLIER TUBE MOUNTING

Figure 8

A side view of the mounting of the photomultiplier tubes on the spectrograph.

ALTERNATE TRIGGER CIRCUIT

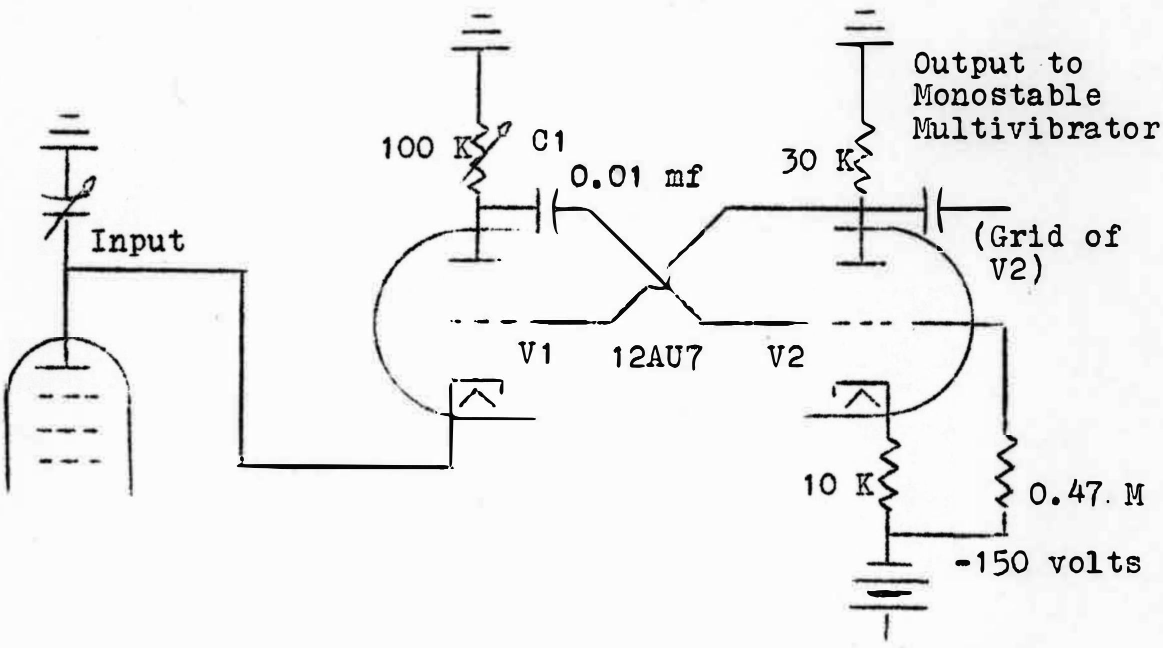


Figure 9

CHAPTER III

ASSOCIATED EQUIPMENT

Sources

Several sources were employed in measuring Faraday rotations. These were:

(1) a sodium source

(2) a d.c. arc source

(3) a mercury source

(4) a tungsten light bulb

(5) a controlled spark source

(6) a xenon source.

The sodium lamp was used when a small monochromatic source was desired. A small d.c. arc source was found to be totally unsuitable because of low intensity in the ultraviolet region and extreme instability. The small mercury light bulb has a strong line at 2536 Å, but too few lines elsewhere to be of significant value in the taking of measurements. The tungsten light bulb was used for one curve from 4250 Å to 7000 Å. A controlled spark source was found to have sufficient intensity in the visible and ultraviolet regions, but lacked the extreme stability needed to take measurements.[6] A xenon source that was constructed for measurements of Faraday rotations showed stability superior to that of the spark source, but lacked the capability of being able to operate for prolonged periods of time.[7] It was found that a source was needed that would be able to operate for continuous periods up to 1 hour. The xenon source that was constructed showed promise as an excellent source of ultraviolet light and was fairly stable, so a commercially built source was purchased. This source is a model 614 Xenon Arc Source available from O. C. Rudolph and Sons, Inc. It has a continuous spectrum from 2000 Å to 7000 Å which is very intense in the visible region but decreases rapidly in intensity as the shorter wavelengths in the ultraviolet region are approached. Figure 10 shows the relative intensity of this source over a portion of its spectral range. The range of intensities shown is 2^8 or approximately 200-fold. The stability of this source was checked by running 9 photographs of its spectrum as nearly identical as possible, then checking the amount of plate blacking with a microphotometer. This procedure was also repeated using the photomultiplier tubes and integrating circuit. The results of these two measurements are shown in Figure 11. This xenon source has been used almost exclusively in obtaining all the data that have been taken.

Polarimeter

The polarimeter used was a model 80 high precision polarimeter constructed by O. C. Rudolph and Sons. The

RELATIVE INTENSITY OF XENON SPECTRUM

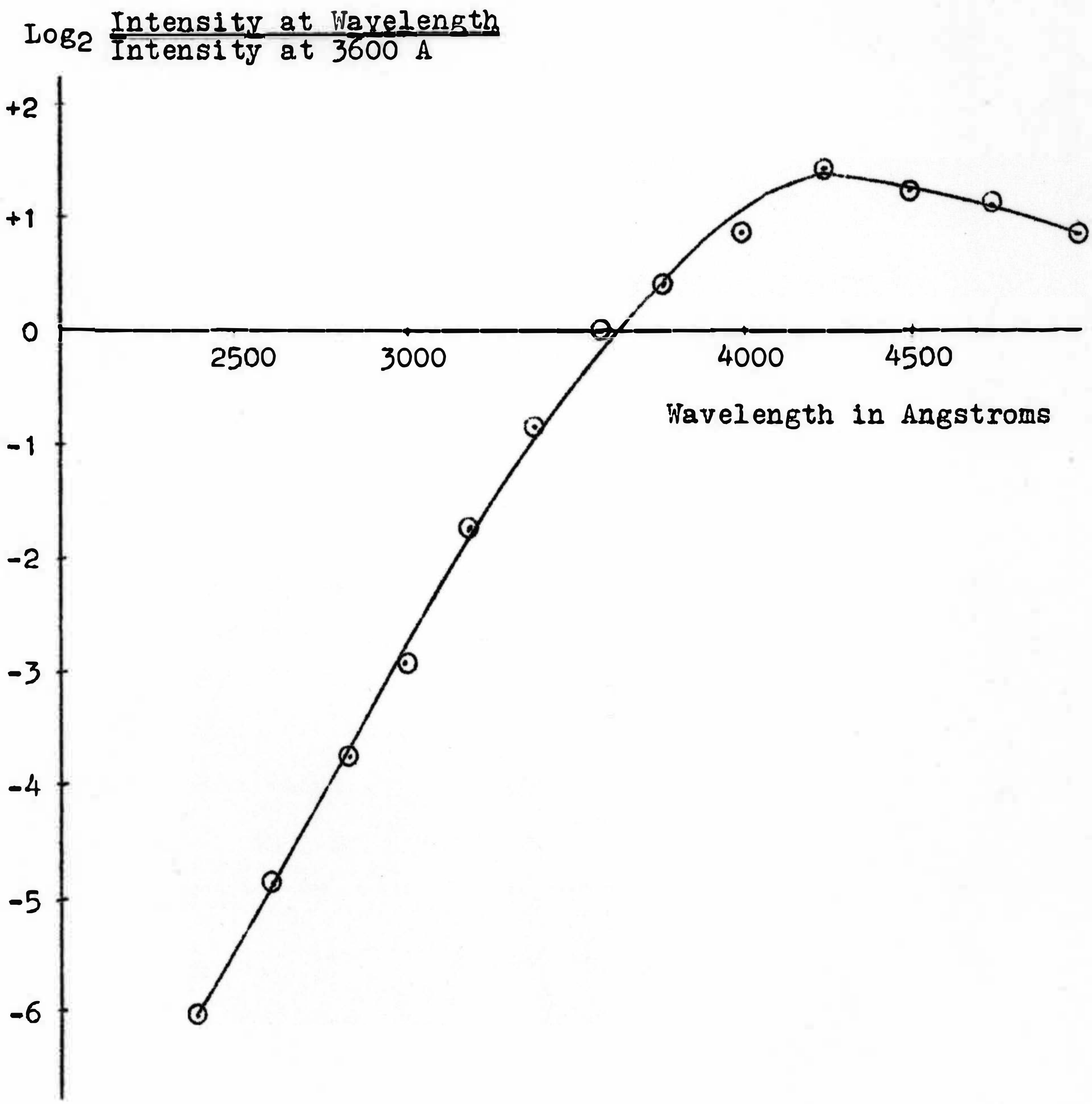


Figure 10

TYPICAL PRECISION MEASUREMENTS

Photographic Plates		Photomultiplier Tubes	
Number of Trial	Reading Microphotometer	Number of Trial	Number of Counts in One Minute
1	31.6	1	189
2	29.8	2	189
3	30.0	3	190
4	30.2	4	189
5	31.0	5	188
6	30.9	6	190
7	31.8	7	189
8	32.1	8	188
9	31.9	9	188
	$\sigma = 0.46$		$\sigma = 0.68$

Figure 11

TYPICAL STANDARD DEVIATION VALUES

Source	Detector	Standard Deviation
Commercial Xenon	Photographic Plate	0.46
Commercial Xenon	Photomultiplier Tube	0.68
Home Made Xenon	Photographic Plate	2.4 (from N. Love thesis)[6]
Controlled Spark	Photographic Plate	5.9 (from N. Love thesis)[6]

Figure 12

ranges of transmission are approximately 2150 Å for the lower limit, and above 8000 Å for the upper limit. The least count of the polarimeter is 0.001° of arc, although this extreme precision has not been necessary in the data taken so far.

Magnet

The magnet consists of two compartments of 1625 turns of number 13 round lacquered-covered wire on an iron spool 5 inches long and 10 inches in diameter. Three helical "pancakes" of copper tubing form the sides of the two compartments. Tap water is run through the tubing during operation of the magnet to cool it and to stabilize the temperature of the sample. This magnet was constructed by The Upjohn Company in connection with research performed on the Faraday effect by that company. The power dissipated in the magnet by a current of 5 amperes is 285 watts. When the pole pieces are in place a 5 ampere current will produce an axial magnetic field of 2850 gauss.

Sample Cells

Sample cells were available in 0.1, 1, 5 and 10 cm lengths. Also, it is possible to use the 0.1 cm cell as a 2.8 cm cell and the 1 cm cell as a 3.7 cm cell providing the 15 mm diameter windows are replaced by 23.7 mm diameter windows. Quartz windows are used when it is desired to work in the ultraviolet region, and glass windows when the range of interest is above 3000 Å. The length of the sample cell inserted in the magnet influenced the magnetic field by the restrictions it placed on the pole pieces which could be used. (See Appendix I)

Spectrograph

The spectrograph used was a Hilger medium quartz cornu prism spectrograph. Its spectral range is 2000-10,000 Å over a focal plane width of 10 inches. Investigation has shown that the dispersion of this instrument can be represented approximately by the formula:

$$d = 1.8 \times 10^9 \ w^{-3}$$

where d is the dispersion in millimeters per angstrom, and w is the wavelength in angstroms. The decreasing dispersion as the longer wavelengths in the visible region are approached make the spectrograph of limited value above 7000 Å.

Vacuum Tube Voltmeter

A vacuum tube voltmeter was used to take some measurements. The type used was a General Radio Company type 1800-B. This instrument has high input impedance (10^9 ohms if the signal being measured is 1.5 volts) when used on the open grid d.c. voltage range.

Typical Operation

The above equipment, when used with the xenon source and photomultiplier tubes, was generally employed with a 5 cm sample cell at a magnetic field of 2850 to 3100 gauss. Temperature of the sample was maintained at approximately 17° C, by the tap water passed through the magnet to cool it.

CHAPTER IV

MEASUREMENTS

It was hoped that the basic method of measuring the Faraday effect could be accomplished with the integrating circuit in the following manner: the photomultiplier tubes were set at the wavelength setting at which the measurements were to be taken. (See Appendix III for description of method used to set the photomultiplier at various wavelengths.) One tube was left fixed at a single wavelength setting while the other tube was used to scan the spectrum. The fixed tube was used to compensate for variations in source intensity and since the two tubes are connected to a common power supply, it provides some compensation for power supply instabilities. With the polarimeter set for maximum transmission and the magnetic field off, the source was turned on and the number of counts registered in one minute was recorded. Then the magnetic field was turned on and the number of counts registered in one minute was recorded.

The plane-polarized light from the polarizer which is incident on the analyzer may be resolved into two components as shown in Figure 13, one parallel to the plane of transmission of the analyzer, and the other at right angles to it.[8] When this light strikes the analyzer set at an angle θ, the component at right angles to it is eliminated while the one parallel to its plane of transmission is passed through. The amplitude A_1 of the light that is passed through the analyzer is, therefore,

$$A_1 = A_0 \cos \theta$$

where A_0 is the amplitude of the incident light. Since intensity is proportional to amplitude squared:

$$I_1 = A_1^2 = A_0^2 \cos^2 \theta$$

$$\text{and } I_1 = I_0^1 \cos^2 \theta$$

where I_0 is the intensity of the incident polarized light. This equation and the relationship it represents are called Malus' law.

RESOLUTION OF PLANE-POLARIZED LIGHT
INTO TWO COMPONENTS

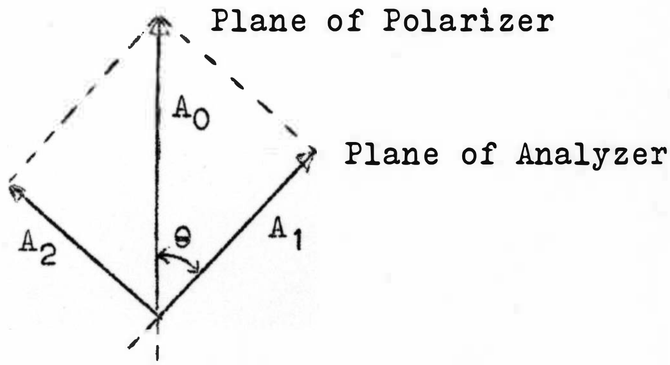


Figure 13

To use this law to compute the rotation, assume I_0 = number of counts registered with the magnetic field off, I = number of counts registered with the magnetic field on, and θ = the angle that the sample has rotated the plane of polarization. The amount of rotation is therefore

$$\theta = \text{arc cos} \sqrt{\frac{I}{I_0}}$$

Figure 14 shows the method used to plot the data that have been obtained. The rotation in degrees is plotted on the vertical axis against the wavelength setting on the horizontal axis. The benzene curve plotted in Figure 14 was obtained using the method of one tube acting as a monitor while the other tube scanned the spectrum. Since the monitor tube measures light which passes through the polarimeter and the magnet, a Faraday rotation may be computed from its readings. Due to the monitor tube measuring light which passes through the polarimeter and magnet, it was not possible to set up a compensation for source variations. It is possible to set up a standard for compensation of source fluctuations for all the magnetic-field on readings or all the magnetic-field-off readings. What is needed is some type of compensation for source fluctuations between a field-on reading at a particular wavelength and the corresponding field-off reading at the same wavelength. To accomplish this, the monitor tube should measure light which is passed around the magnet and the analyzer. A chopper disk mounted between the polarizer and the magnet could be used to reflect part of the light into the monitor tube and let the remainder of the light pass through the

BENZENE CURVE USING INTEGRATING CIRCUIT

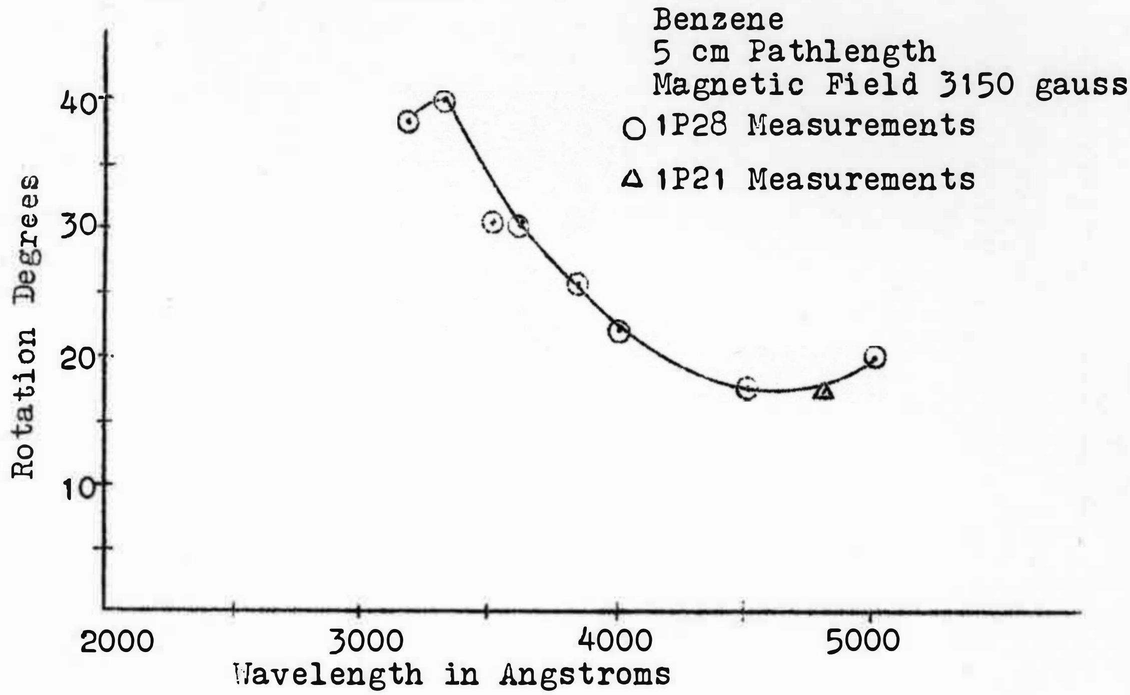


Figure 14

COMPARISON CURVE - $ZnSO_4$

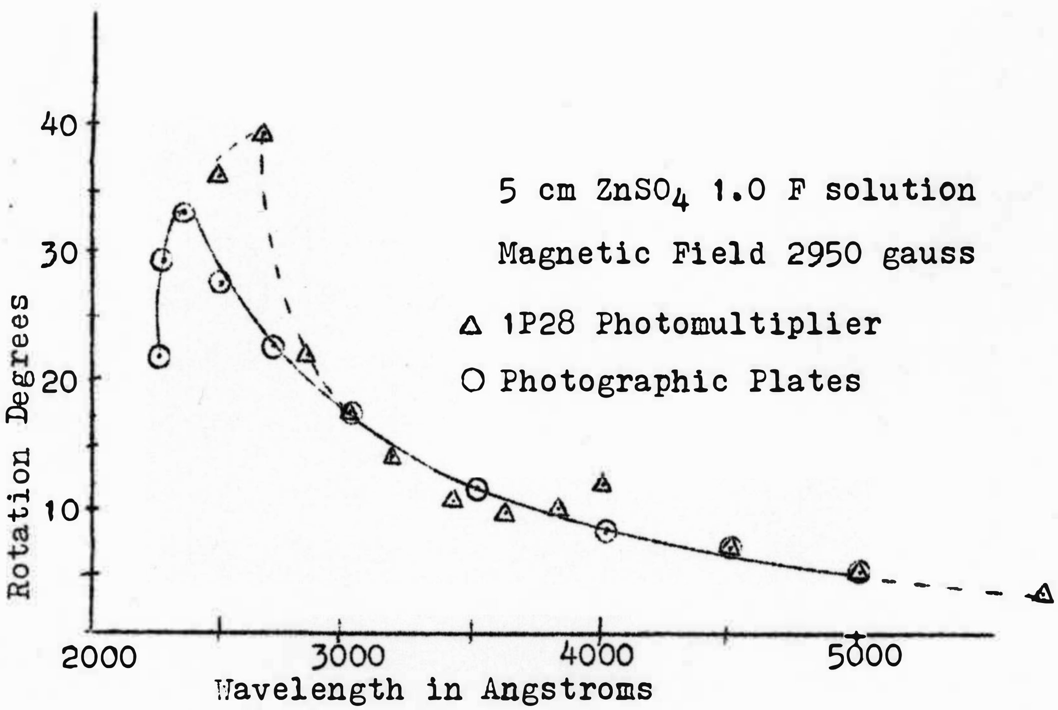


Figure 15

magnet to the other tube. A second spectrograph or a narrow band pass filter would be necessary if the light is to be monitored at some particular wavelength. An objection against this arrangement, with or without a second spectrograph, is the loss of light intensity due to the chopper disk.

Figure 15 shows two curves, one taken with photographic plates as a detection device, the other curve using a 1P28 photomultiplier tube as a detection device. The curve taken with photographic plates is shown as a means of evaluating the accuracy of the photomultiplier method. Another comparision spectra of a 0.5 F $NiSO_4$ solution is shown in Figure 16. Although the sample path lengths are different, the observed rotation patterns are not significantly changed. $NiSO_4$ has a strong absorption region from 3700 Å to 4300 Å. The difference in positioning of the peaks and absorption edges is due to two reasons:

(1) poor determination of the wavelength at which the photomultiplier tube is set,

(2) loss of signal near the absorption edge when using the photomultiplier tube.

The data taken with the photographic plates is much more accurate than the photomultiplier tube data. It is generally difficult to measure angles of 10 degrees or less with the integrating circuit. At angles of 10^{o} or less the $\cos^2\theta$ factor in Malus' law becomes very close to 1.

COMPARISON CURVE - $NiSO_4$

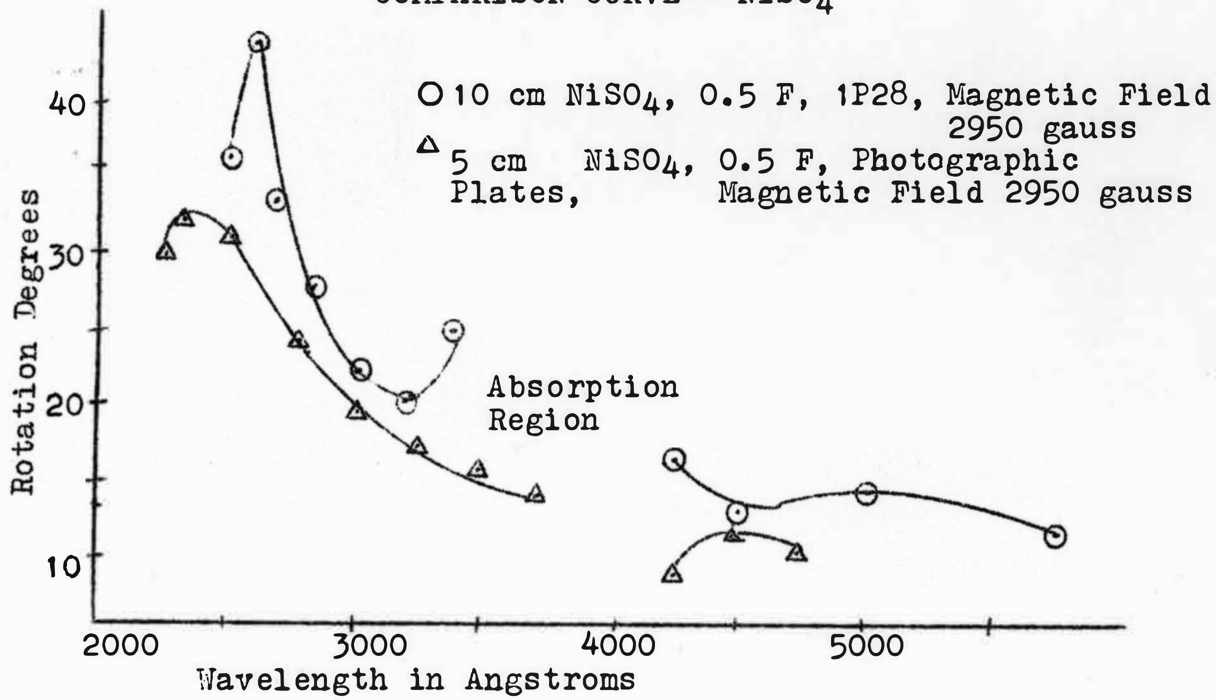


Figure 16

DATE TABLE FOR $NiSO_4$ CURVE

Wavelength	(I_0) Number of Counts With Field Off	(I) Number of Counts With Field On	Exposure Time	Rotation in Degrees Computed
5750	213	209	1 Min.	8.2
5000	466	452	"	10.2
4500	328	317	"	9.6
4250	152	144	"	13.3
3400	79	69	"	22.9
3200	248	227	"	17.4
3000	258	228	"	19.9
2800	167	136	"	25.9
2700	92	65	"	32.8
2600	68	34	"	45.0
2500	57	37	"	36.4

Figure 17

For instance, $\cos^2 5^{\circ} = 0.992$. This means that if with the magnetic field off, 100 counts are registered, then 99 counts should be registered with the magnetic field on. Any small instability that would push the field-on reading up to 100 or down to 98 would result in an error in the amount of rotation measured. Although it would appear that the answer to this problem would be to increase the counting rate, when the counting rate is increased to more than 500 counts per minute, the integrating circuit becomes unstable. It was found advisable when using the circuit to keep the number of counts below 300 counts per minute. The number of counts limits the smallest angle that may be measured. In the above example the two readings were 100 and 99 respectively, which corresponds to an angle of 6° rotation. If the actual angle of rotation was 4°, the number of counts with the field on and off could both be 100, which means that an angle of 4° cannot be measured with a total number of counts of 100. Any instabilities in the power supply, source, or in lengths of exposure make the measurements of small angles more difficult.

The decrease in source intensity of the xenon source as the lower wavelengths are approached makes measurements of large rotations troublesome. Low source intensity leads to the signal becoming extinguished before the polarimeter is rotated 90 degrees from the point of maximum transmission. Figure 18 shows the departure of

CALIBRATION OF THE INTEGRATING CIRCUIT

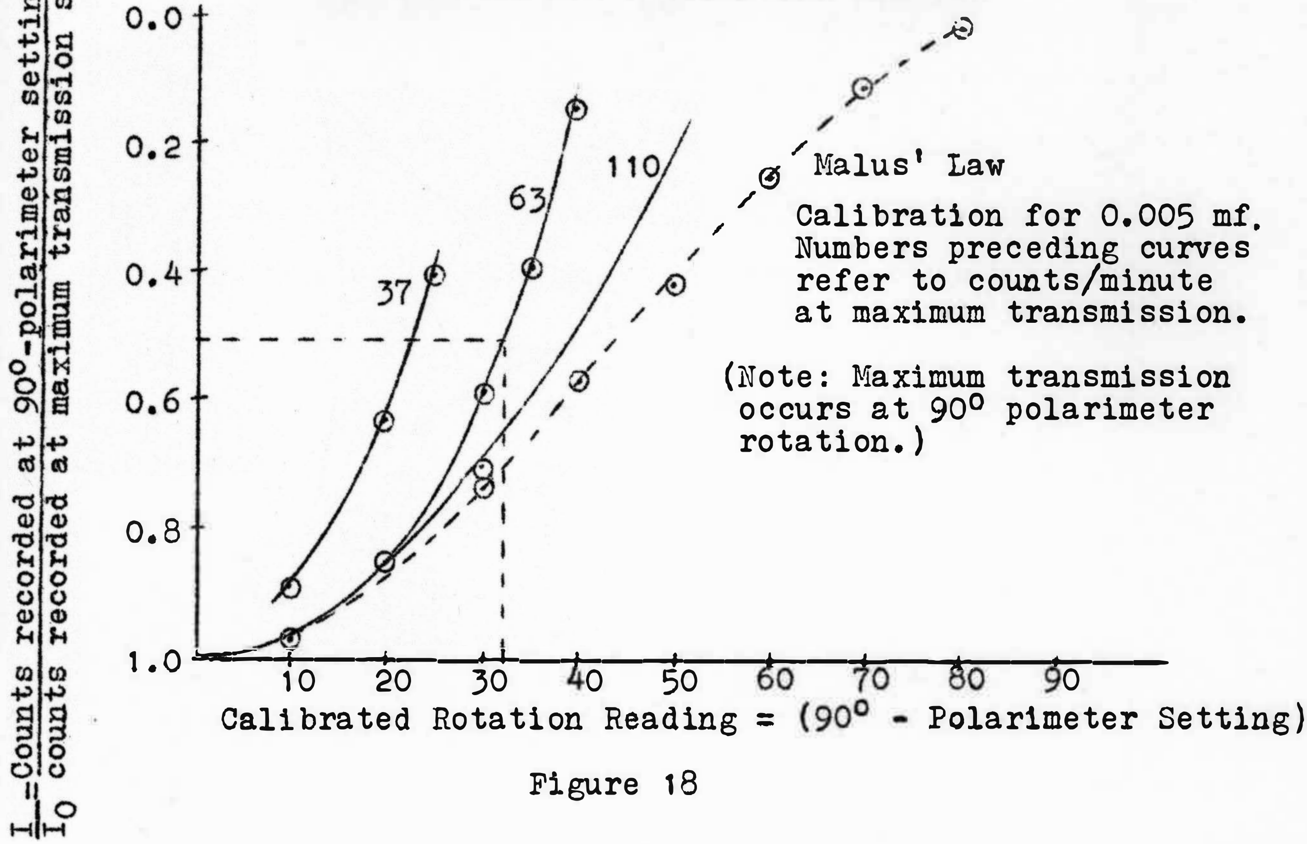


Figure 18

CALIBRATION OF $NiSO_4$ CURVE OF FIGURE 16

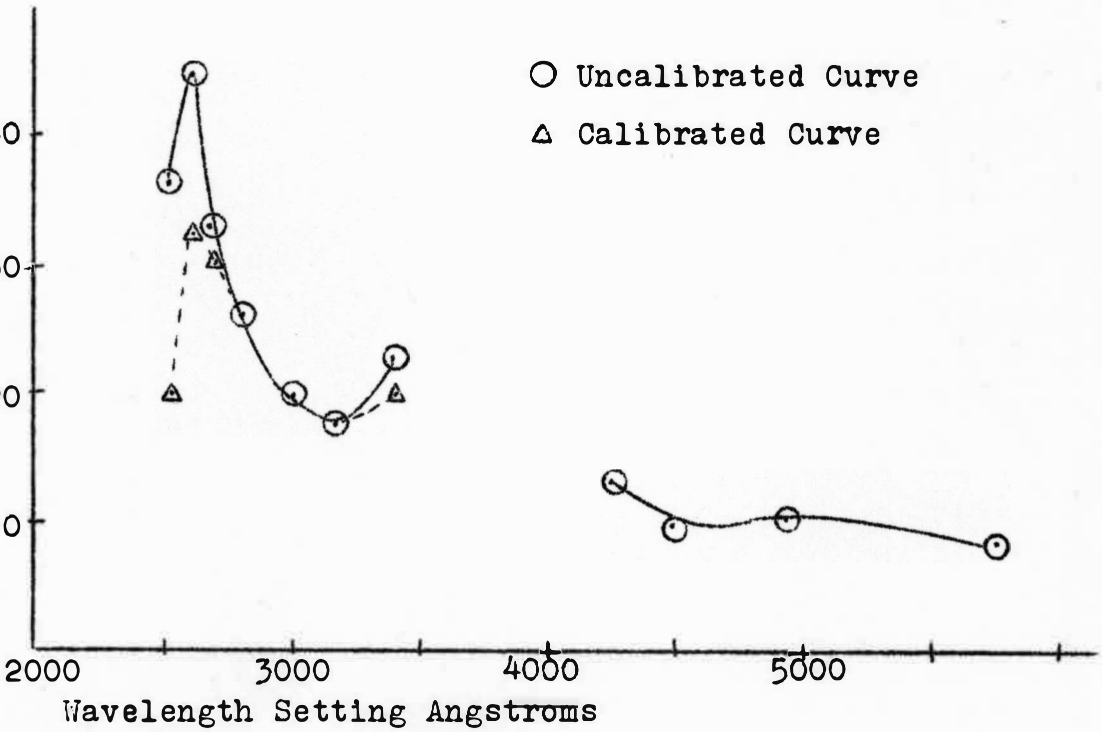


Figure 19

the integrating circuit response from Malus' law. These calibration curves are plotted in a manner which facilitates computation of rotations. The calibration curve of Figure 18 has been used to correct those points of the NiSO4 curve of Figure 17 which have small counting rates. As an example of the use of the calibration curve, consider the 2600 angstrom point of the $NiSO_4$ curve. The number of counts recorded with the field off was $I_0 = 68$, and with the field on was $I = 34$. $I/I_0 = 34/68 = 0.50$. To obtain the calibrated rotation reading, read up the ordinate to where $I/I_0 = 0.50$. Then read across to the intersection of the 0.50 ordinate line and the 63 count line. The abscissa of the intersection of the 0.50 ordinate line and the 63 count line is the calibrated rotation reading. The two dotted straight lines in Figure 18 illustrate the calibration method. Since 67 is close to 63, the 63 count line was used. In most cases it will be necessary to interpolate between the calibration curves. From the calibration curve, it is evident that when the source intensity is low, a large rotation may not be detected when the magnetic field is turned on. It is believed that graphs of the type shown in Figure 18 will be needed to make the method of measurements previously described successful.

In an effort to improve the accuracy of the measurements, a null method was tried. Measurements are taken in the following manner: with the magnetic field off, the source is turned on and the polarimeter rotated until no counts are registered in a 10 second period of time. The polarimeter setting is recorded. The polarimeter is rotated toward the other side of the no response zone until the circuit starts to count again, then reversed until no counts are recorded in a 10 second period of time. These two settings represent the two thresholds of counting about the point of minimum transmission. These two settings are added and divided by two to find the point of minimum transmission or the zero point. Once the zero point has been determined, the magnetic field is turned on and the above procedure repeated. Since the plane of polarization is rotated with the field on, the zero point is also rotated. Once the zero point is computed with the field on, the zero point with the field off may be subtracted from it to find the amount of rotation. The approach to the zero point is always from the side where the circuit is counting. This is so the capacitor in the current integrator is always charged.

Figure 20 shows two curves taken with this method. One is Thoulet's solution (see Appendix III), the other one Potassium Iodide. A data table is shown in Figure 21 for the Thoulet's solution curve. The rotations for the entire KI curve are less than 10^{o}, while the rotations for the Thoulet's solution curve are all larger than 29^{o}.

POTASSIUM IODIDE AND THOULET'S SOLUTION

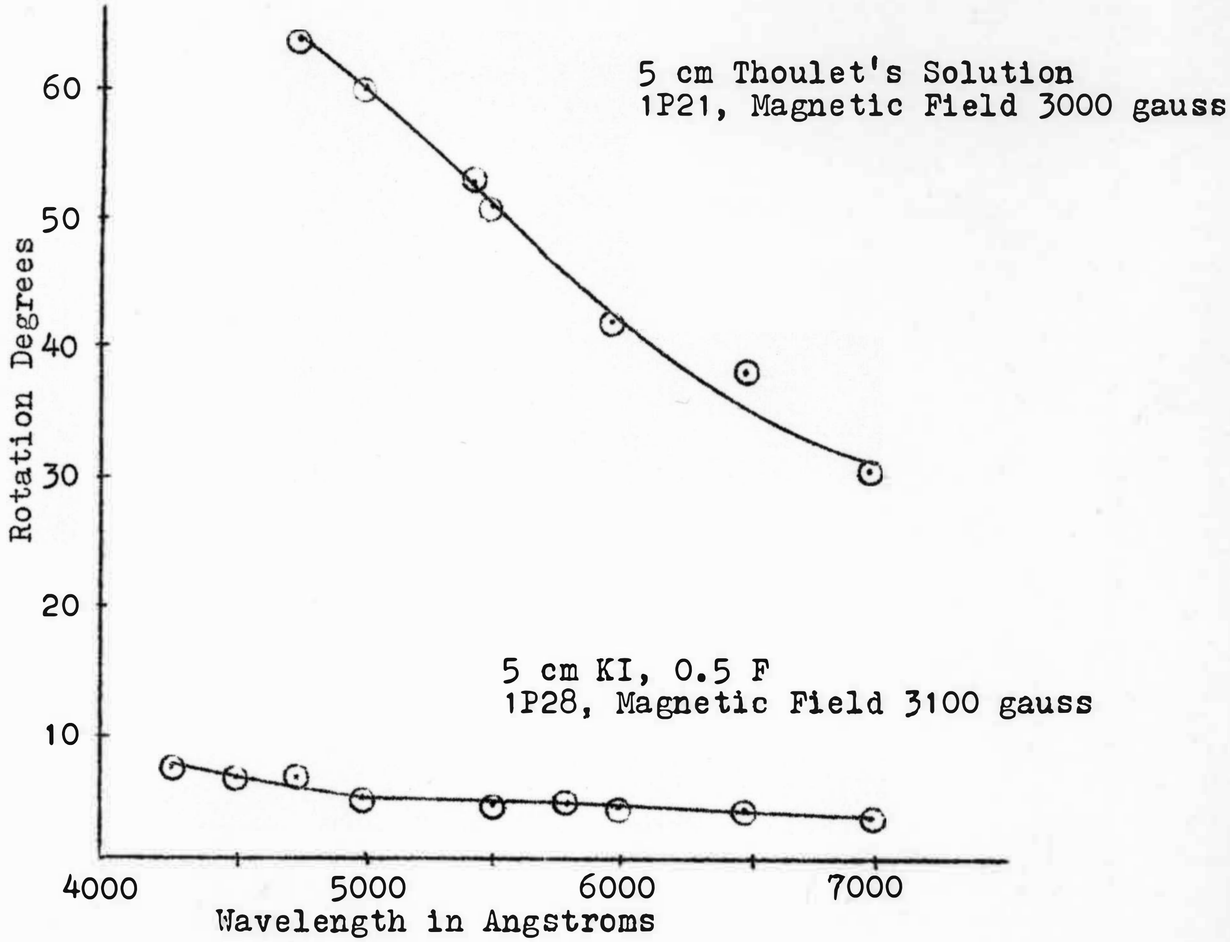


Figure 20

DATA FOR THOULET'S SOLUTION CURVE

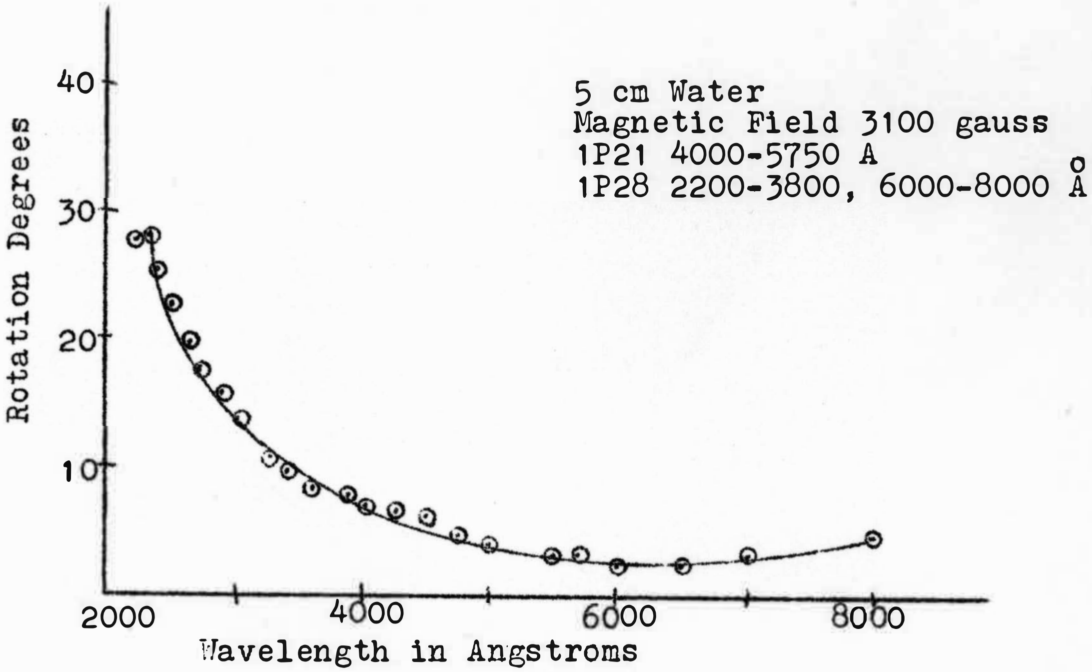
Angstroms	Zero, one Side	Zero other Side	Sum	½ Sum	Rotation Degrees
5461 Zero Point	- 6.75	- 3.25	3.50	1.75	
5461	60.5	49.0	109.5	54.75	53.0
5500	49.0	57.0	106.0	53.0	51.25
5000	41.25	84.0	125.25	62.50	60.75
4750	38.0	-86.0	132.0	66.0	64.25
6000	47.0	39.0	86.0	43.0	41.25
6500	40.5	39.25	79.25	39.75	38.0
7000	24.5	39.5	64.0	32.0	30.25
8000	15.0	46.5	61.5	30.75	29.0

Figure 21

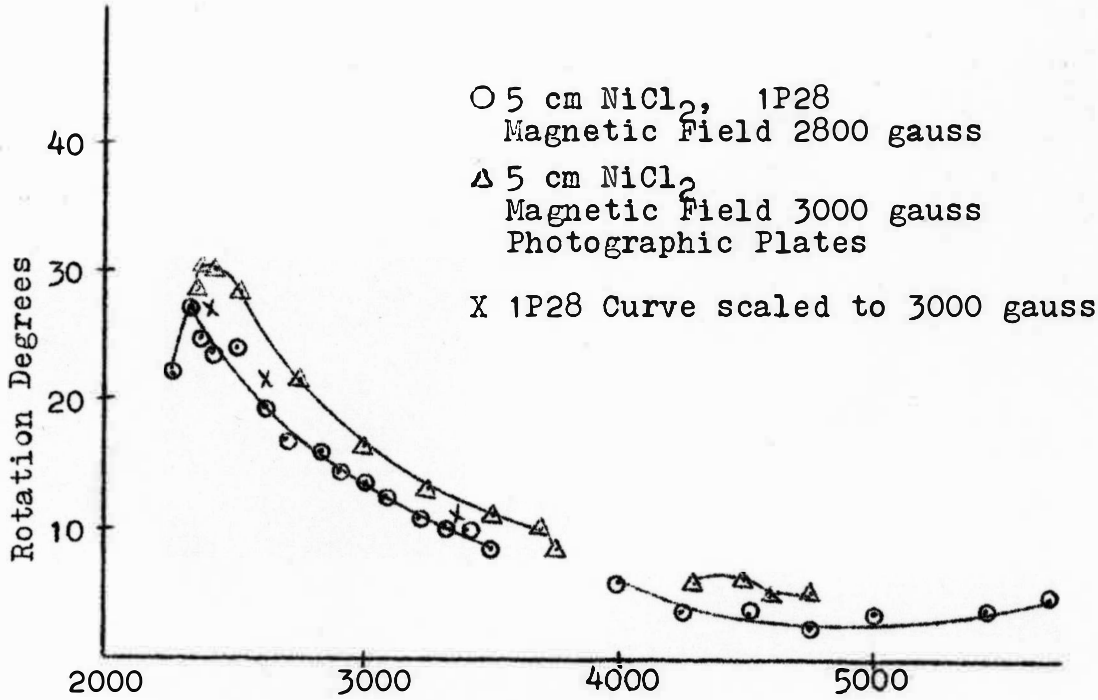
If the source intensity is sufficiently high, rotations down to 2^{o} may be measured with little difficulty. Figure 22 displays two curves taken with this method. The wavelength scales on curves (a) and (b), when compared with other data, appear to be inconsistant and should be shifted to the right. To shift the curve, the displacement in angstroms from the other curve is found at one wavelength. A dispersion curve is then used to find the amount the curve should be shifted at other wavelengths. Figure 22 (b) shows a comparison curve between photographic plates and the 1P28 photomultiplier tube for $NiSO_4$. Part of the difference in rotation can be accounted for by the difference in the magnetic field. Three points are shown on the curve for which the difference in magnetic field is compensated for. The displacement of the peaks and absorption edges may be due to improper wavelength settings of the photo-multiplier tube. However, the large rotations in the regions of low intensity have been eliminated by the null measurement method. Figure 23 shows two benzene curves taken with the null method under identical conditions. The wavelength scale on these two curves are displaced from each other.

The accuracy of the null method is estimated as being within $\pm$ 2 degrees of the true rotation when the source intensity is sufficiently high. A sufficiently high source intensity would correspond to an ordinate

NULL METHOD CURVES



(a) Water Curve



(b) $NiCl_2$ Curve, Comparison Between Photographic Plates and Null Method

Figure 22

BENZENE CURVES

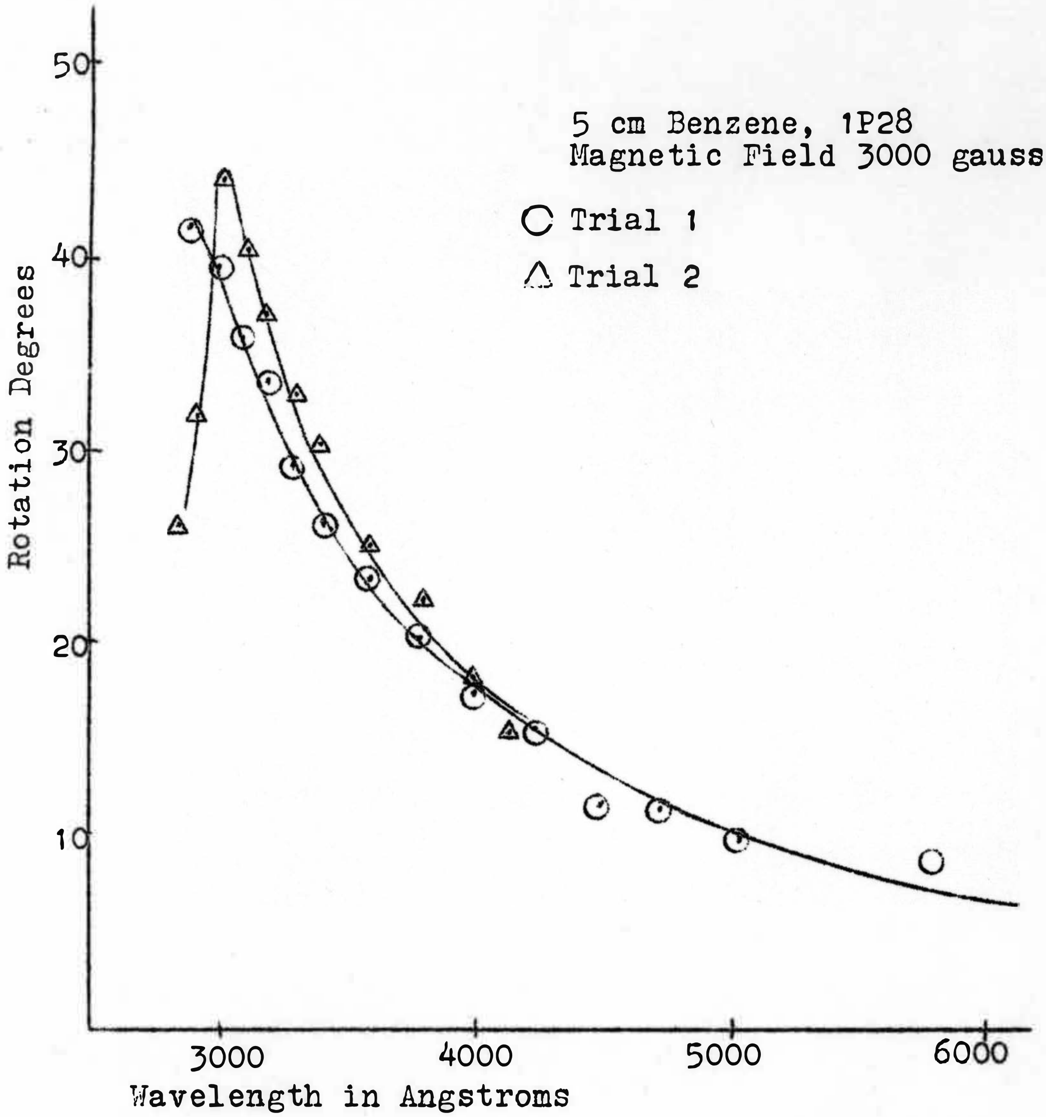


Figure 23

value of -4.5 or higher on the graph of the xenon source shown in Figure 10. This ordinate value corresponds to a wavelength of 2650 Å. At this wavelength, a measurement of the $ZnSO_4$ curve shown in Figure 15 by the Null method would be expected to have a maximum error of 2^{o} divided by 23^{o}, or about 9%. (The 23^{o} value of the $ZnSO_4$ curve is taken from the photographic plate curve in Figure 15 at 2650 Å). The Malus' law curve shown in Figure 15 measured the rotation at 2650 Å as being 29^{o}. This is an error of 6/23 or 26%. The above two sample values show that in a region of low light intensity, the Null method is superior. A comparison of the two methods shows that the speed of taking data is about equal, but that the Null method is more reliable. With the Null method, it is possible to measure large or small rotations at either high or low light intensities with little difference in the numbers of degrees error. One disadvantage of the Null method is the long time the magnetic field is on. The coils in the magnet become heated, which increases their resistance. This increased resistance reduces the current through the coils, decreasing the magnetic field and the amount of rotation. Use of a current regulator in the magnet power supply circuit would correct this defect.

Another method, utilizing a vacuum tube voltmeter, was also tried. Figure 24 is a circuit diagram of the arrangement.

VACUUM TUBE VOLTMETER METHOD

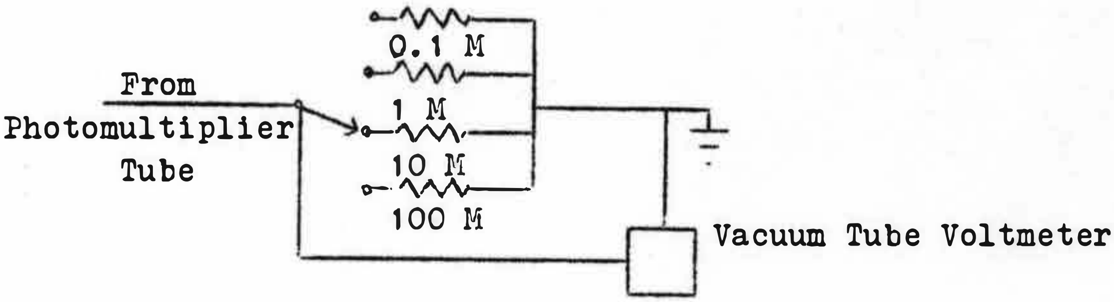


Figure 24

A vacuum tube voltmeter is used to measure the potential drop across a large resistor. The polarimeter is set at maximum transmission, and voltmeter readings taken with the field on and the field off. From these readings, the rotation is computed.

Figure 25 shows a Thoulet's Solution curve taken using the vacuum tube voltmeter method. The curve taken by the Null method is plotted on the same graph for comparison. Figure 26 is the data table for the vacuum tube voltmeter curve. The dark current reading is taken in between the magnetic-field-on reading and the magnetic-field-off reading. Before using the law of Malus to compute the rotation, the dark current must be subtracted from both of the other readings. This method shows some improvement over the use of the integrating circuit Malus law method. However, it does not follow Malus' law either. Some type of calibration would be needed with this arrangement. The vacuum tube

THOULET'S SOLUTION VACUUM TUBE VOLTMETER MEASUREMENTS

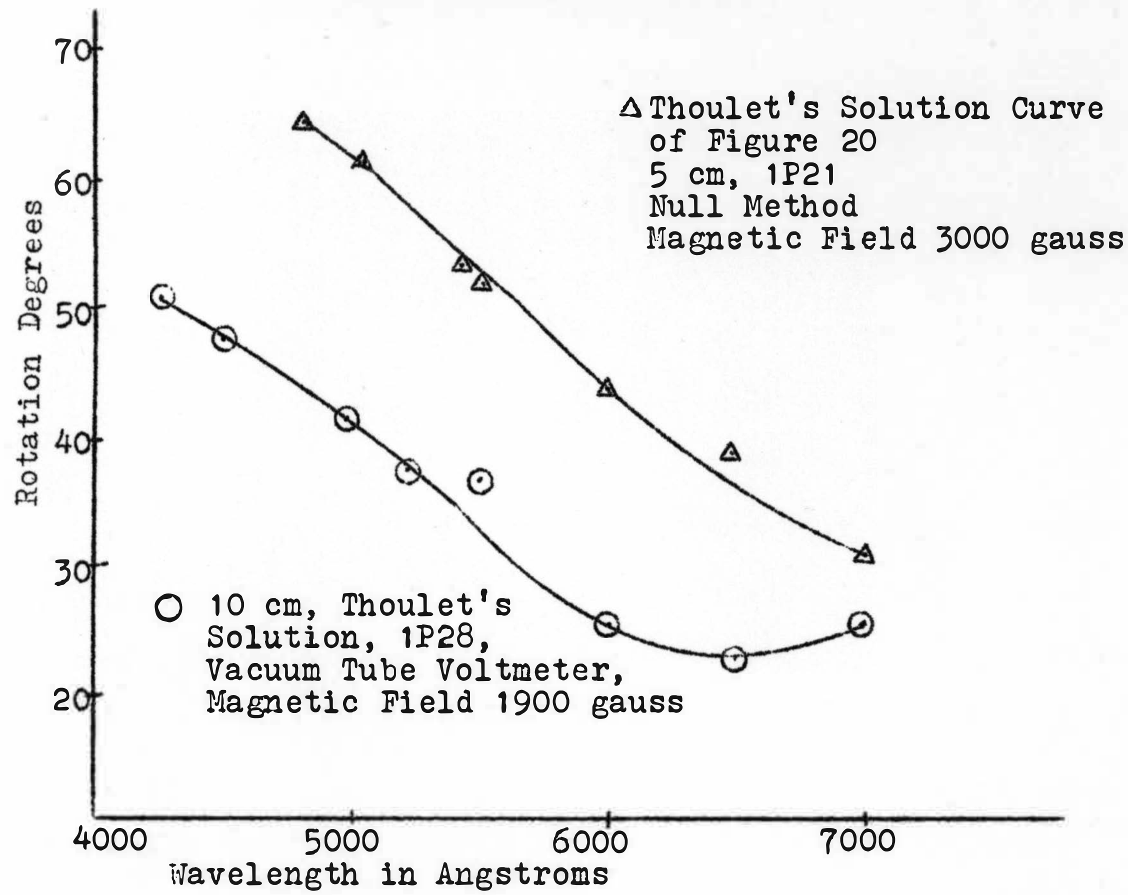


Figure 25

DATA TABLE FOR VACUUM TUBE VOLTMETER CURVE IN FIGURE 25

Wavelength Angstroms	Dark Current Rdg	Reading: Field Off	Reading: Field On	Rotation Computed
7000	2.18 volts	3.05 volts	2.89 volts	25.4 degrees
6500	2.40	5.80	4.30	22.4
6000	0.21	0.60	0.53	25.1
5500	0.20	3.90	2.60	36.6
5000	0.15	4.20	2.50	41.2
4750	0.15	1.90	1.00	45.5
4500	2.90	3.75	3.28	48.1
4250	2.70	2.95	2.80	50.9

Figure 26

voltmeter method of taking data is faster than either the Null method or the Malus law method. Figure 27 shows the departure of the vacuum tube voltmeter method from the law of Malus. The agreement is much better than with the integrating circuit. Figure 27 could be used as a calibration curve in the same manner as explained for the integrating circuit calibration curve.

A null method was tried with the vacuum tube voltmeter. This method consisted of finding the zero point with the field off, then finding the zero point with the magnetic field on. By subtraction of the two zero points, the amount of rotation is determined. The method used in finding the zero point is not to find the actual point of minimum transmission, but to find the polarimeter setting at a fixed voltage on each side of the zero point. An example would be: the acual null voltage is 6.3 volts. The polarimeter is rotated until the reading is 6.5 volts. This polarimeter setting is recorded. Then the polarimeter is rotated to the other side of the zero point until a reading of 6.5 volts is obtained. From the two polarimeter settings the zero point is determined. It is easier to find the polarimeter settings at some predetermined voltage than to find the null voltage. This is due to the voltages changing much more rapidly per degree of polarimeter rotation away from the null region than they do near the null region. Figure 28 is a $CuSO_4$ curve taken in the manner

DEPARTURE OF VACUUM TUBE VOLTMETER
MEASUREMENTS FROM MALUS LAW

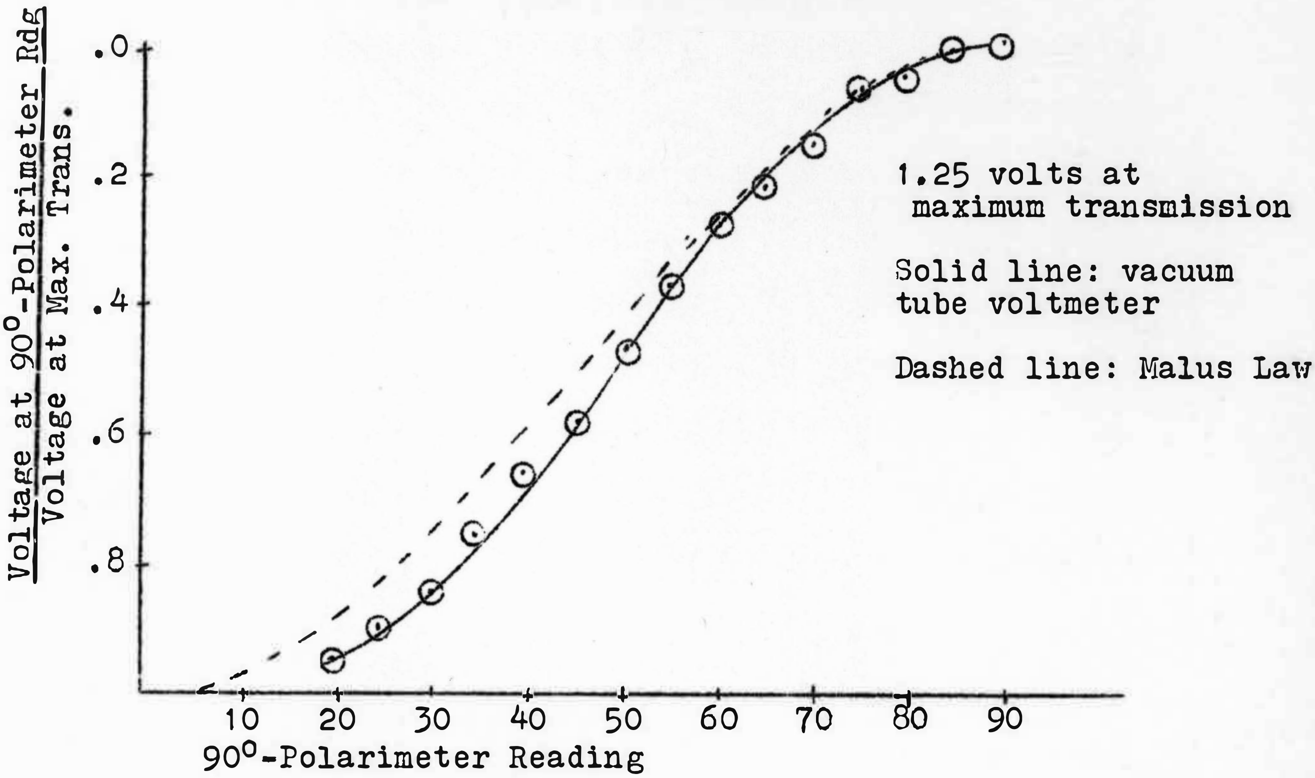


Figure 27

$CuSO_4$ CURVE

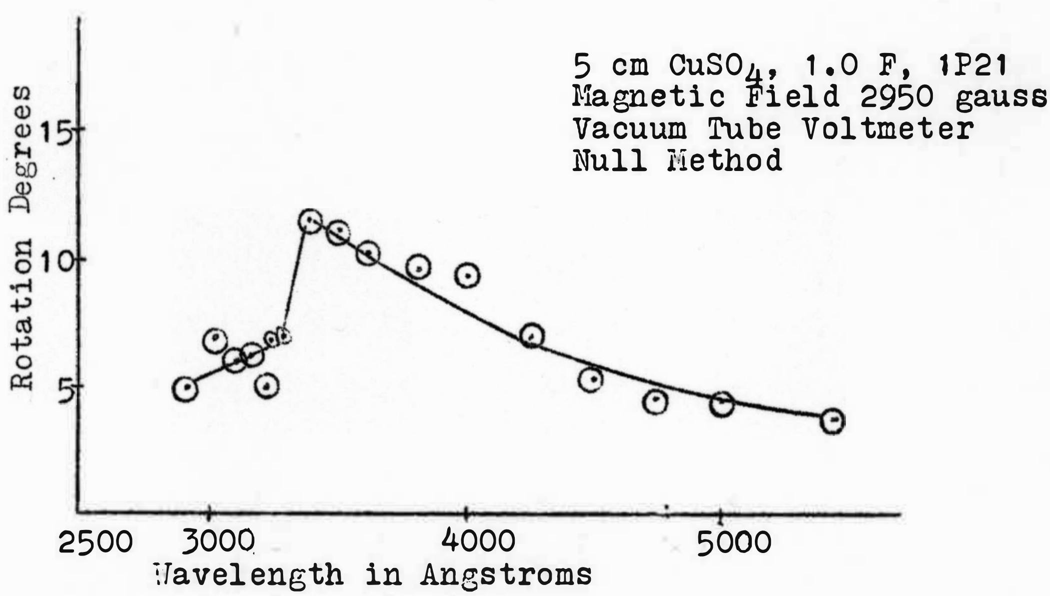


Figure 28

described above. This method of taking measurements was not as accurate as hoped for. The changes in voltages for small polarimeters rotations were not large enough for accurate determinations of the polarimeter readings. An example would be: at a polarimeter setting of 20^{o} and a maximum signal of 3.7 volts, a 0.2 volt change in voltage requires a 4.5^{o} polarimeter rotation.

One additional way of measuring rotations, a half-deflection method, was accomplished with the vacuum tube voltmeter. Measurements were taken with the following procedure: with the magnetic field off, the polarimeter was rotated until it read 45^{o}, and the source turned on and the voltage reading on the vacuum tube voltmeter recorded. Then the magnetic field was turned on and the polarimeter rotated until the voltage reading on the voltmeter scale was exactly equal to the reading obtained with the field off. The polarimeter reading with the field off is subtracted from the polarimeter reading with the field on to find the amount of rotation. The reason for choosing 45^{o} for the field off polarimeter setting is that the change in voltage reading degree polarimeter rotation is a maximum at 45^{o}. This may be easily proven by differentiating Malus' law twice with respect to θ, and setting $d^2I/d\theta^2$ equal to zero to find the point where the slope changes at a maximum rate. This proof is shown below:

Voltage reading (V) is directly proportional to the intensity of the radiation incident on the cathode. Therefore $V = kI$, $V_0 = kI_0$, and Malus' law is written

$$V = V_0 \cos^2 \theta = V_0 \frac{1 + \cos 2\theta}{2}$$

$$\frac{dV}{d\theta} = -V_0 \sin 2\theta$$

$$\frac{d^2V}{d\theta^2} = -2V_0 \cos 2\theta \quad \text{(condition for a maximum change of slope)}$$

$$0 = \cos 2\theta \quad 2\theta = 90^\circ, 270^\circ, 450^\circ \ldots$$

$$2\theta = \frac{2n + 1}{4} \times 360^\circ$$

Here only the solution corresponding to $n = 0$ is of interest. This solution is of course $360^\circ/8$ or 45°.

If the voltage reading at maximum transmission is known, the change in voltage reading per degree of polarimeter rotation may be computed from the formula for the slope of Malus' law.

$$\frac{\text{volts}}{\text{radian}} \quad \frac{dV}{d\theta} = -V_0 \sin 2\theta$$

Division of both sides of the above equation by 57.3° gives the formula for calculation of the voltages changes per degree of polarimeter rotation.

$$\frac{1}{57.3^\circ} \frac{dV}{d\theta} = -V_0 \frac{\sin 2\theta}{57.3^\circ}$$

At 45° the above equation yields the following result:

$$\frac{1}{57.3^\circ} \frac{dV}{d\theta} = \frac{-V_0}{57.3^\circ}$$

For a signal of 30 volts at maximum transmission, the change in voltage reading per degree of polarimeter is

30/57 = 0.52. Actual measurement of a 30 volt signal yields the result that 1.85^o of polarimeter rotation was needed for a 1 volt change in signal at 45^o. $1/1.85 = 0.542$ which is within 4.2% of the theoretical value. This method will work at polarimeter settings other than 45^o, but the change in voltage reading per degree of polarimeter rotation will be smaller and the accuracy of the reading will decrease accordingly.

Figure 29 (a) is a table of four substances whose rotation was measured at the sodium wavelength by the procedure described above. A sample table of values is provided for the toulene measurement. Accuracy of the reading is estimated as being within $\pm$ 3/4 degree of the true rotation. Figure 29 (c) is a water curve taken using a 40 watt tungsten light bulb as a source. A change in procedure used on the water curve was to set the polarimeter at a setting with the field on in one direction, then reverse the field and match the original voltage by rotating the polarimeter. This doubles the difference between the two readings, and by algebrically subtracting them from each other, the amount of rotation is obtained. The advantage of this method is that the division by two cuts errors in half. A $CoCl_2$ curve (see Figure 30) was taken by the half-deflection method using the xenon source. The precision of the half-deflection method points on the $CoCl_2$ curve is estimated as being within $\pm$ 2^o of the true rotation. A $CoCl_2$ curve

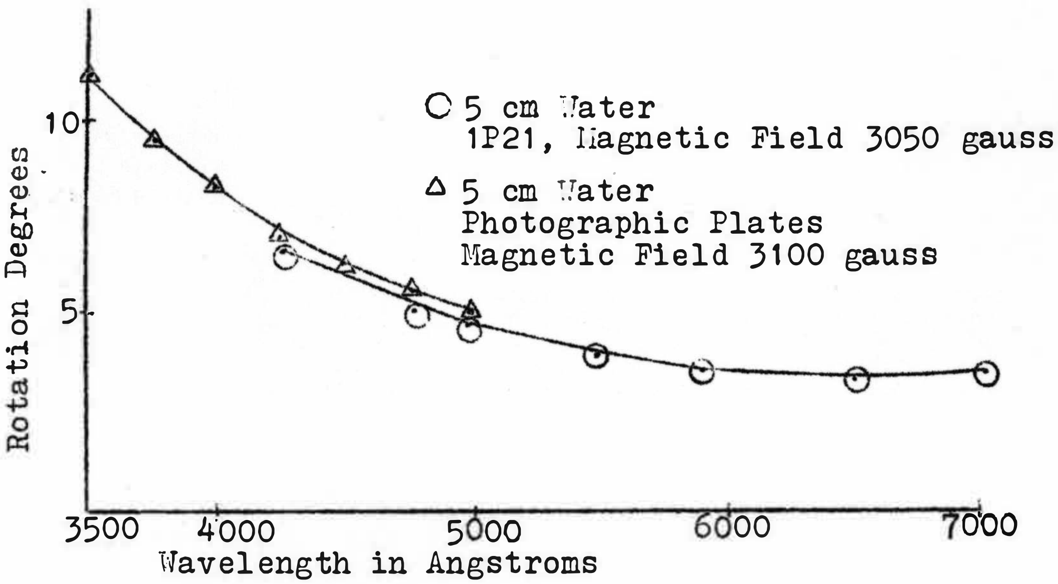
HALF-DEFLECTION DATA

Substance	Path Length	Observed Rotation	Magnetic Field
Carbon Disulphide	5 cm	10.8°	3050 gauss
Toulene	5 cm	6.7	3050
Thoulet's Solution	1 cm	5.5	3050
Water	5 cm	3.6	3200

(a) Four substances at the sodium lamp wavelength of 5893 A

Trial	Initial Polarimeter Setting	Rotation to Restore Original Reading	Rotation
1	45°	51.4°	6.4°
2	"	51.6	6.6
3	"	51.8	6.8
4	"	52.2	7.2
5	"	51.7	6.7

(b) Toulene Data For Rotation Measurement



(c) Water Curve Taken With A Tungsten Light Bulb

Figure 29

taken with photographic plates is plotted on the same graph as a comparison. The xenon source is not stable enough to use this method if precision of greater than $\pm 2^{\circ}$ is desired.

Compared with the other methods, and assuming that a stable light source comparable to the 40 watt tungsten light bulb is available, this method is superior to the others in accuracy. It is believed that with two measurements at each point, a precision of $\pm 1^{\circ}$ can be achieved by using this method. Several sizes of capacitors from 0.01 microfarads to 10 picofarads were connected across the terminals of the vacuum tube voltmeter to stabilize it against small changes in the input signal. The 0.01 and 0.005 microfarad capacitors each improved the stability by a small amount. One difficulty of this method is that the voltage divider mounted on the base of the photomultiplier tube heats up the tube, which causes a small increase in dark current. This increased dark current causes a slow drift in the voltage reading which causes an error in the polarimeter setting if not compensated for. A second difficulty is the extreme stability that the source, photomultiplier tube power supply, and vacuum tube voltmeter must have. One example of the effect of source intensity is: at a 45° polarimeter setting, a rotation of 3.2° produced a voltage change of 0.2 volts. Since the signal at maximum

$CoCl_2$ COMPARISON CURVE

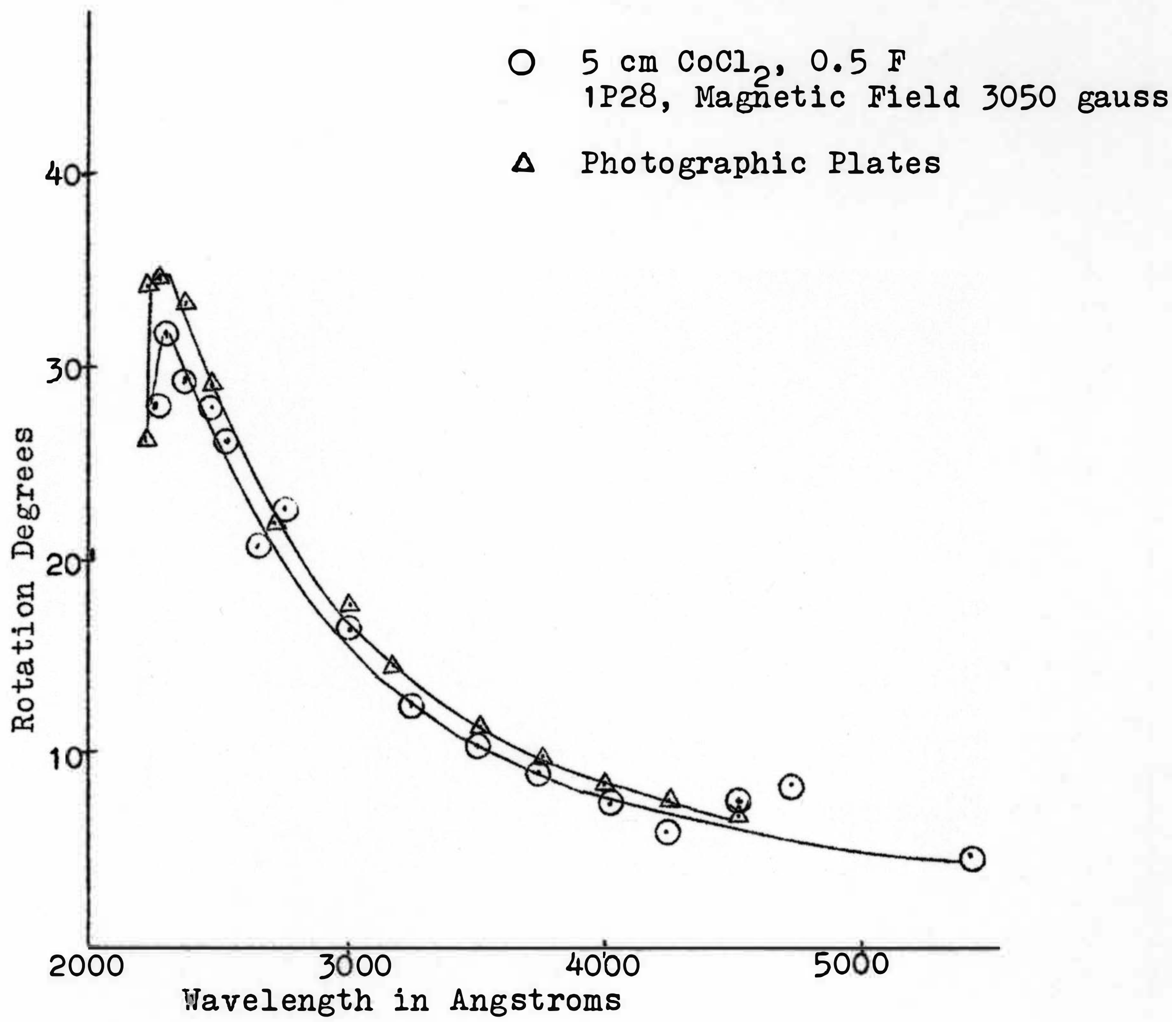


Figure 30

transmission was 4.4 volts, a change of 1.1% in source intensity would produce a 0.05 volt change in the voltage reading, and a 0.8^{o} change in polarimeter setting would be needed to compensate for it. Therefore, if the source intensity changed by 1.1% during a measurement period, an error of 0.8^{o} would result. Both the sodium lamp and the tungsten bulb have stability of 0.5% which is sufficient to take measurements with.

The vacuum tube voltmeter is more sensitive than the integrating circuit. A current of 5×10^{-10} amperes may be detected with the vacuum tube voltmeter. It is estimated that the integrating circuit can detect a current of 5×10^{-8} amperes. Because of the dark current, the two lowest scales (0.5 and 1.5 volts) on the vacuum tube voltmeter, when connected across the largest resistor (10^{8} ohms), cannot be used. If it were possible to cool the photomultiplier tubes, the lowest detectable current would be 5×10^{-11} amperes. The precision of the other readings would also be increased.

Several of the curves (Figures 15, 16, 22, 23, 28 and 30) show a decrease of rotation at the lower wavelengths. The decrease of rotation is associated with increased absorption by the sample. This fall-off of rotation has been observed previously on liquids.[9]

It has also been observed in solid-state materials in the infrared region.[10] Therefore, it is believed that the decreased rotation is a real phenomenon, and not caused by the low light intensity encountered in absorption edges.

CHAPTER V

CONCLUSIONS

A two channel counter has been constructed and the experiment it was designed for tried. Since the use of the counters in a two channel mode of operation was not a total success, several alternate methods were attempted. Some of the alternate methods show promise of measuring the rotation to a fair degree of accuracy. However, not any one of the methods is as accurate as the photographic plate method. The Half-deflection method has accuracy of $\pm$ 1 degree when used with a stable source. When used with the xenon source, Null methods have an accuracy of $\pm$ 2 degrees, which is an improvement over the Malus law method. Calibration of the integrating circuit or of the vacuum tube voltmeter would improve the Malus law method.

All of these methods are substantially faster than using photoplates as detection devices. The water curve shown in Figure 22 (a) took 1 3/4 hours to take the data. An additional 1 1/4 hours was used in the setting up of equipment, computing the rotations and plotting the curve. To obtain a complete curve using photographic plates, it is often necessary to take more than one plate. If only one plate was required to take a complete curve, then the methods would be approximately equal in the amount of time required to obtain the data.

Total running time of the source is higher when using photoplates. All of the photomultiplier methods require longer magnetic current running times. The Null methods have the magnet "on" throughout almost the entire set of readings. The magnet being "on" a large amount of time results in some fluctuations in readings due to magnetic current instabilities.

The sensitivities of the various methods ranked in order from the highest sensitivity to the lowest are: (1) Photographic Plates; (2) Vacuum Tube Voltmeter Malus law Method; (3) Vacuum Tube Voltmeter Null Method; (4) Half-Deflection Method; (5) Integrating Circuit Null Method; (6) Integrating Circuit Malus Law Method.

The accuracies of the various methods with the xenon source from the most accurate to the least accurate are: (1) Photographic Plates; (2) Null Methods; (3) Half-Deflection Method; (4) Vacuum Tube Voltmeter Malus Law Method; (5) Integrating Circuit Malus Law Method.

Future experimentation with photomultiplier measurement of the Faraday effect should consider the following areas for improved performance: (1) More accurate method of wavelength determination, (2) more stable power supply, (3) cooling the photomultiplier tubes, and (4) use of more sensitive measuring apparatus such as electrometer tube circuits.

APPENDIX I

Figure 27 shows the monostable multivibrator and the driver tube for the mechanical register. By proper adjustment of the 2.5 megohm potentiometer, a large plate current will flow through V2. This current flowing through the 10,000 ohm cathode bias resistor cuts off almost all current flowing through tube V1. The potential at the plate of V1 nearly assumes that of the battery supply voltage. Typical voltages at various points in the circuit under quiescent conditions are shown in Figure 31.

The firing of the neon bulb induces a positive potential on the grid of V1. This causes a small amount of plate current to flow which reduces the potential at the plate of V1. This initiates a switching action which causes the monostable stable multivibrator to go through one complete cycle. Because of the return of the grid of V2 to the battery supply voltage through a large resistor, the grid at the completion of one cycle is at a higher potential than the cathode. The large current flowing through V2 permanently cuts off V1, since its grid is at ground potential.

The output is taken off of the plate of V2 through a 0.1 microfarad capacitor. During the quiescent state of the circuit, the potential at the plate of V2 is

MONOSTABLE MULTIVIBRATOR AND MECHANICAL REGISTER DRIVER CIRCUIT

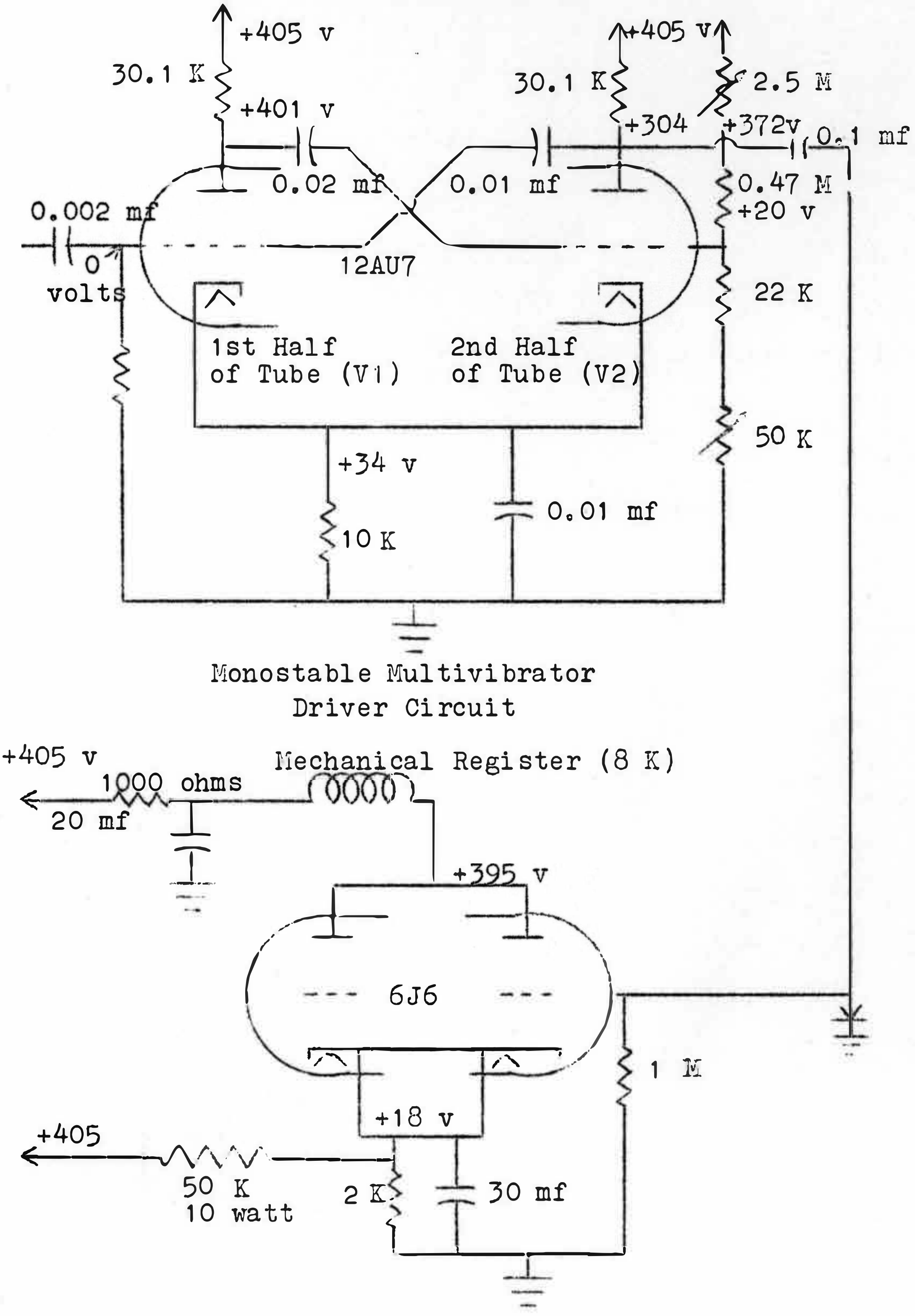


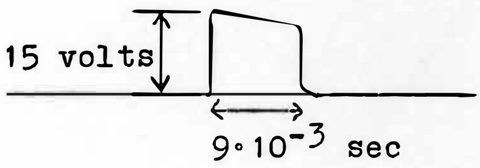
Figure 31

reduced by 100 volts to plus 305 volts. When the tube is cut off during a cycle of operation, the potential rises to + 405 volts. At the conclusion of the cycle, the potential falls back to + 305 volts. From the above values it is easily seen that the output is a positive pulse. Figure 32 (a) shows a drawing of the output. If the grid-bias resistor to ground (50,000 ohms) is improperly adjusted, a wave form of the type shown in Figure 32 (b) will result. This frequently results in the mechanical register tripping more than one count per pulse. Once the circuit is in an operating range, very little adjustment is needed.

The output pulse from the monostable multivibrator raises the potential of the grid of the 6J6 causing a large plate current to flow which trips the mechanical register. The purpose of the 50,000 ohm, 10 watt voltage dropping resistor in the cathode circuit of the 6J6 driver tube is to prevent the grid of the tube from becoming positive with respect to the cathode.

The length of the output pulse from the monostable multivibrator was measured as being 9×10^{-3} seconds. This was found to be the shortest pulse that will reliably operate the mechanical register. The maximum number of pulses that the register can count per second is 25. This corresponds to one pulse every 4×10^{-2} seconds.

OUTPUT PULSES



(a) Proper Waveform

(b) Improper Waveform

Figure 32

APPENDIX II

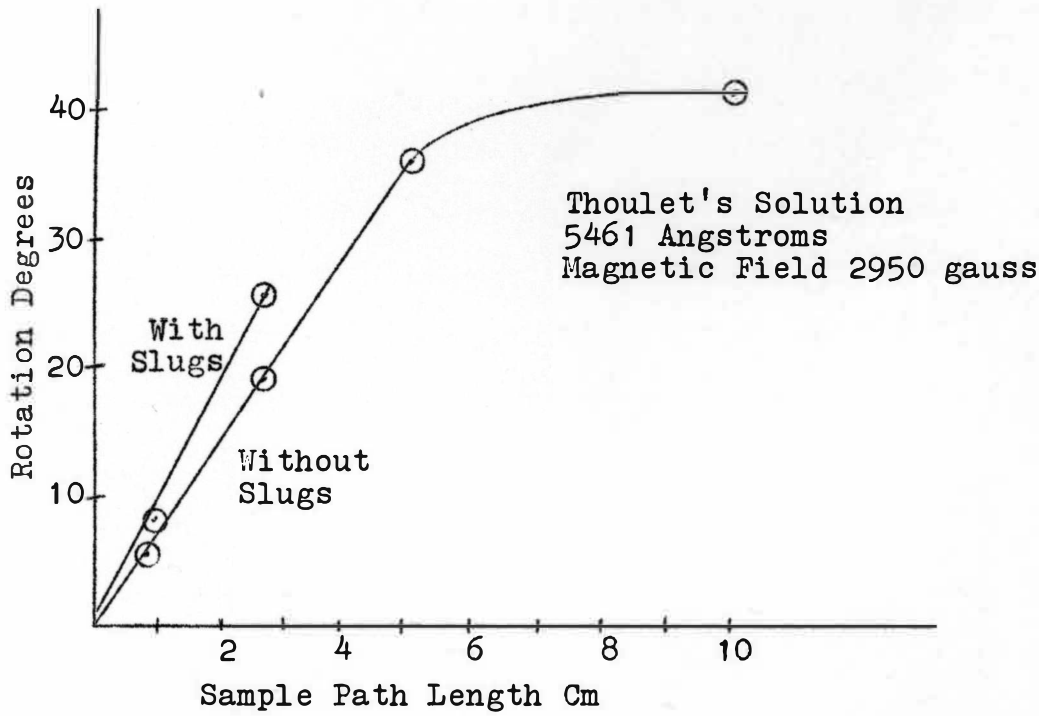


Figure 33

The decrease of rotation when using the 10 cm path length is due to a weakening of the magnetic field when the 10 cm sample cell is in the magnet. Insertion of the 10 cm cell requires the use of shorter pole pieces in the magnet. The curve marked "with slugs" refers to two short cylindrical pieces with holes drilled through their center which are fitted between the sample cell and the pole pieces to intensify the magnetic field.

APPENDIX III

Three spectral lines were used to initially set the photomultiplier tubes at a wavelength setting. These were: the 5750 Å yellow band between the red and green bands of a tungensten light bulb, the 2536 Å line of a small mercury light bulb, the 5461 Å green line of another mercury source, and the sodium lamp wavelength of 5893 Å. Once one of these lines was used to obtain a setting, the lateral displacement from the corresponding setting on the wavelength scale was measured. This displacement was used to find any subsequent setting.

APPENDIX IV

Thoulet's solution is prepared by heating 270 grams of HgI_2 and 230 grams of KI in 80 ml of distilled water in a porcelain evaporating dish on a water bath. The color of the prepared solution should be a transparent yellowish green. A few drops of mercury are added to prevent iodine from slowly separating and darkening the color.[11]

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