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POLARIZATION EFFECTS IN OPTICAL
DIFFRACTION

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Robert Louis Gault
1953



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**POLARIZATION EFFECTS IN OPTICAL
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M. S. degree in Physics

C. D. House

Major professor

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POLARIZATION EFFECTS
IN OPTICAL DIFFRACTION

by

Robert Louis Gault

A Thesis

Submitted to the School of Graduate Studies of
Michigan State College of Agriculture and
Applied Science in partial fulfillment
of the requirements for the
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Robert F. Gault

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I. INTRODUCTION

When unpolarized light is scattered by a sharp straight edge, it is possible to observe a polarization in the diffracted light. This effect was first described by Gouy and Wien in the 1880's.¹ Arnold Sommerfeld's mathematically exact solution for the problem of diffraction of electromagnetic waves by a straight edge, which explained the polarization effect, was published in 1896.² Later observations of the effect were made by Jentsch³ in 1927, using traditional optical methods. These observations were in close agreement with the predictions made by Sommerfeld.

Interest in general diffraction theory has been stimulated in the last few years by the development of the technology of micro waves. Other contemporary technological developments have made it possible to make measurements of optical phenomena (particularly those of low intensity) by means other than the traditional ones. In view of these two facts, it seems pertinent to re-investigate some particular aspects of the straight-edge diffraction phenomena.

This paper deals with some observations of the polarization effect produced by the diffraction of light by a straight-edge and by a narrow slit. The theoretical discussion begins with the general results predicted by Sommerfeld, and is carried

out in detail to show the polarization intensity ratio to be expected for light diffracted by a straight-edge. In addition an approximate treatment for the polarization by a slit is included.

Observations were made by means of the electron photomultiplier tube. The results agree with Sommerfeld's theory as closely as may be expected, and for the best measurements made, show a slight disagreement with the observations of Jentsch.

The investigation has turned out to be a very interesting one, and as experimental projects are wont to do, has led the author into many unexpected problems as well as many surprising and educational observations.

II. THEORY OF DIFFRACTION OF LIGHT BY A HALF-PLANE

A. The Sommerfeld Theory

Sommerfeld's exact solution of the problem of diffraction of electromagnetic waves by a semi-infinite, perfectly conducting half-plane is one of the outstanding examples of the application of mathematical ingenuity to the theoretical treatment of a physical problem. Despite the ingenuity of the method, the solution has so far been of restricted usefulness. It has not been found applicable to any but this one very particular problem -- that of the diffraction of light by a half-plane. (In this paper the word "light" will be used interchangeably with the phrase "electromagnetic radiation", but it must be realized that Sommerfeld's theory is not restricted to visible radiation).

The problem at hand involves the solution of the wave equation with the boundary conditions appropriate to a conducting half-plane. If the screen (the half-plane) is a perfect conductor, then the necessary boundary condition is that the tangential component of the electric field must vanish everywhere on the screen. A three dimensional coordinate system may be defined, in which the screen occupies all the points included in the x - z plane for which x is positive. Thus the edge of the screen lies along the z -axis, and the material of the screen lies behind the edge, in the x - z plane.

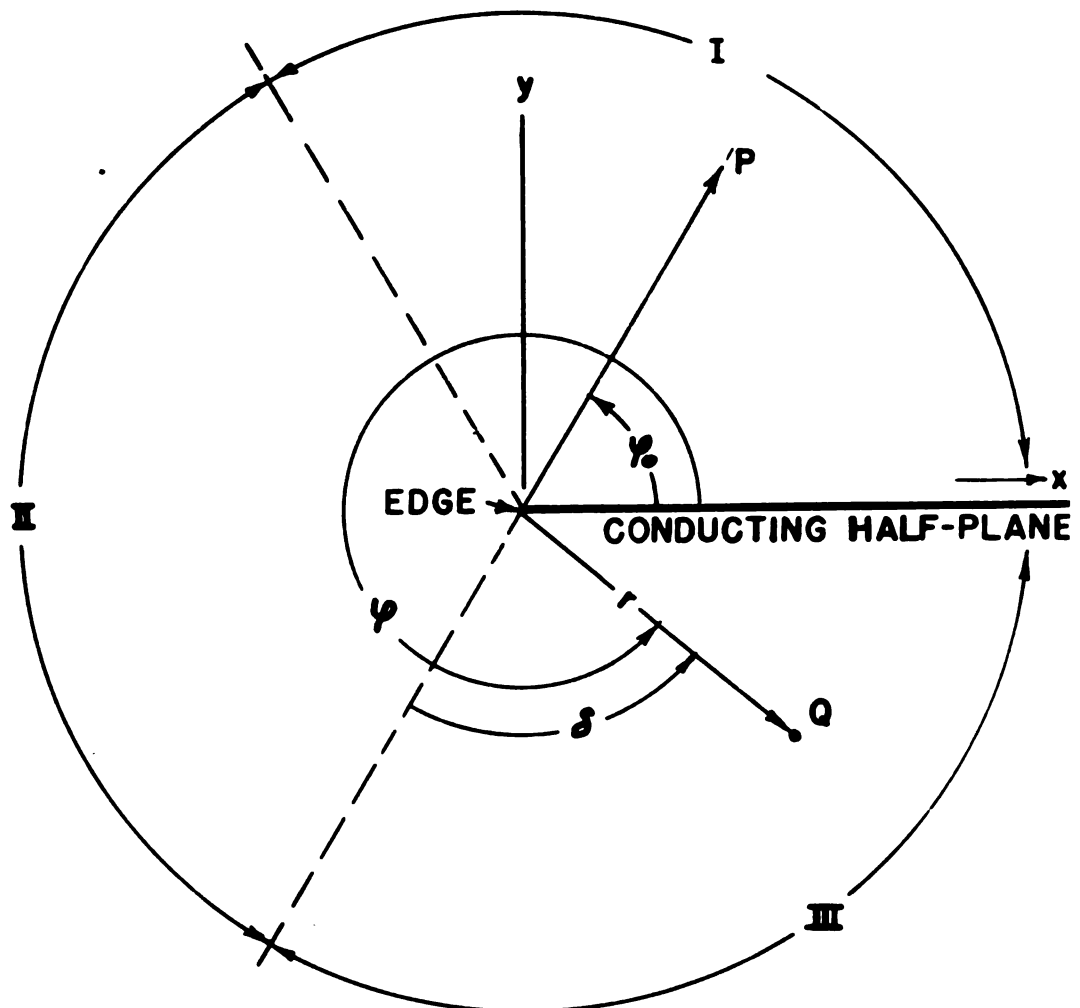
It would be a simple matter to satisfy the necessary boundary conditions if the screen occupied the whole of the x - z plane. The method would be similar to the method of images used in solving electrostatic problems. That is, if one considers a line source of electromagnetic radiation parallel to the z axis and placed so that it intersects the positive y -axis at an infinite distance from the origin, the condition for vanishing of the tangential component of the electric field on the x - z plane can be satisfied by merely imagining another line source, equal to but out of phase with the first, (and polarized in the same direction) placed parallel to the z -axis, so that it intersects the negative y -axis at an infinite distance from the origin. This makes the tangential component of the electric field vanish at every point of the x - z plane, whereas for the problem at hand it is desired to make it vanish only on half of the plane. Sommerfeld's solution involves such an "image" type of solution, but requires the use of a two-sheeted Riemannian surface to insure that the electric field vanishes only on the half plane occupied by the conducting screen. This argument is carried out in a straight forward fashion in Born's Optik.⁴ The theoretical material which follows is based upon the results of the Sommerfeld theory.

It is found that the solution depends on the state of polarization of the incident light. Since a line source parallel to the half-plane is being considered, it is evident

that the situation is one which is not dependent on z , and which can therefore be considered a two dimensional problem. Figure 1 shows the x - y plane, in which the positive x -axis represents the intersection of the screen with the x - y plane, the point P represents the intersection of the line source with the x - y plane, and the point Q represents the position of the observer at a distance r from the edge. The angle φ_0 is the angle of incidence of the plane waves from P , while the angle φ is the angle of diffraction. Both angles are measured in a counter-clockwise direction from the positive x axis.

Since the source is at an infinite distance from the edge, the disturbance caused by it is a plane wave, polarized either parallel to the line of the source (hereafter referred to as the π case) or perpendicular to the line of the source (hereafter referred to as the σ case). The strength of the source is such that without the interference of the half-plane, the amplitude of the disturbance is unity. The effect of inserting the half-plane into this plane wave disturbance is to change the form of the disturbance. The resultant disturbance takes on three distinct forms, as may be seen in the three divisions of the space in Figure 1.

The first section (the reflection region) is one in which the net disturbance consists of the incident plane wave,



- P:** Source at infinite distance
Q: Observer at finite distance
I: Reflection region
II: Unshadowed region
III: Shadow region

FIG. 1 - COORDINATE SYSTEM OF THE SOMMERFELD THEORY.

a reflected plane wave, and a cylindrical wave radiating from the edge of the half-plane. In the second region (unshadowed), the net disturbance consists of the incident plane wave plus the cylindrical wave from the edge; while in the third region (the shadow region), the only disturbance is that due to the cylindrical wave from the edge. For a unit amplitude incident wave the amplitudes of these disturbances take the following forms:

$$\begin{array}{ll}
 \text{I Reflection region:} & \\
 u_{\pi, \sigma} = \cos[kr \cos(\varphi - \varphi_0)] \mp \cos[Kr \cos(\varphi + \varphi_0)] + Z & \\
 \text{II Unshadowed region:} & \\
 u_{\pi, \sigma} = \cos[kr \cos(\varphi - \varphi_0)] + Z & (1) \\
 \text{III Shadow region:} & \\
 u_{\pi, \sigma} = Z = \frac{1}{4\pi} \sqrt{\frac{\lambda}{r}} \left[\cos(kr + \frac{\pi}{4}) \right] \left[\pm \frac{1}{\cos(\frac{\varphi + \varphi_0}{2})} - \frac{1}{\cos(\frac{\varphi - \varphi_0}{2})} \right] &
 \end{array}$$

where the term Z represents the cylindrical wave, and k is the propagation constant, equal to $\frac{2\pi}{\lambda}$. Where there is a choice of signs, the upper sign corresponds to the π case while the lower sign corresponds to the σ case.

This problem will be primarily concerned with that part of the disturbance which is the cylindrical wave. It is convenient to use the terms "inflection angle" and "deflection angle" when discussing this wave. The former refers to the diffraction angle for light which is diffracted into the region of the geometric shadow, while the latter refers to the diffraction angle for light which is diffracted into the non-shadow

region. The former is measured counter-clockwise from the extension of the line of propagation of the incident wave, and the latter is measured clock-wise from the same line. In other words, if the observer stands in the geometric shadow he sees inflected light; while if he stands in the unshadowed region, he sees deflected light from the edge (in addition to the direct light from the source).

If one observes this phenomenon qualitatively, it may be seen that it behaves as predicted by Sommerfeld. If one stands in the shadow region and observes the edge which is illuminated by a narrow source parallel to the edge and at a reasonably large distance (50 cm. or so) from it, the edge will appear to be the source of radiation. If the direction of polarization of the incident light is changed, the apparent intensity of this source changes. It appears most brightly illuminated when the light is polarized perpendicular to the edge. An important fact here is that the edge appears⁵ to be the source of the diffracted light. Just the inverse polarization effect is observed in the light diffracted into the unshadowed region. In order to see the effect in the latter case, it is necessary to exclude light coming directly from the original source to the observer.

B. Mathematical Expression for Polarization Ratio

If one takes the expression from equations (1) for the amplitude in the shadow region and divides the amplitude for

parallel polarization by that for perpendicular polarization, then squares the resultant ratio, there results an expression for the ratio of intensities of the parallel to the perpendicular polarization components:

$$\frac{Z_{\pi}}{Z_{\sigma}} = \frac{\cos\left(\frac{\varphi - \varphi_0}{2}\right) - \cos\left(\frac{\varphi + \varphi_0}{2}\right)}{\cos\left(\frac{\varphi - \varphi_0}{2}\right) + \cos\left(\frac{\varphi + \varphi_0}{2}\right)}.$$

Upon expansion and simplification this expression leads to the equation

$$\frac{Z_{\pi}}{Z_{\sigma}} = -\tan \frac{\varphi}{2} \cdot \tan \frac{\varphi_0}{2}. \quad (2)$$

Therefore the polarization intensity ratio is:

$$\frac{I_{\pi}}{I_{\sigma}} = \left(\tan \frac{\varphi}{2} \tan \frac{\varphi_0}{2} \right)^2. \quad (3)$$

This expression holds for the cylindrical wave in both the shadow and non shadow regions.

When (3) is written for an inflection angle equal to δ , where $\delta = \varphi - \varphi_0 - \pi$, $\delta \geq 0$,

$$\frac{I_{\pi}}{I_{\sigma}} = \cot^2\left(\frac{\pi}{4} + \frac{\delta}{2}\right). \quad (4)$$

For deflection at an angle $-\delta$,

$$\frac{I_{\pi}}{I_{\sigma}} = \frac{1}{\cot^2\left(\frac{\pi}{4} + \frac{\delta}{2}\right)}. \quad (6)$$

These relationships may be derived as follows:

Let $\varphi_0 = \frac{\pi}{2}$ (the case of normal incidence),

then from (3), $\frac{I_{\pi}}{I_{\sigma}} = -\left(\tan \frac{\varphi}{2} \tan \frac{\pi}{4}\right)^2 = \tan^2 \frac{\varphi}{2}$.

Since $\varphi = \frac{3\pi}{2} + \delta$, $\frac{I_{\pi}}{I_{\sigma}} = \tan^2\left(\frac{3\pi}{4} + \frac{\delta}{2}\right)$,

$$\text{then } \frac{I_{\pi}}{I_{\sigma}} = \left(\frac{-\tan \frac{3\pi}{4} + \tan \frac{\delta}{2}}{1 - \tan \frac{3\pi}{4} \cdot \tan \frac{\delta}{2}} \right) = \left(\frac{1 - \tan \frac{\delta}{2}}{1 + \tan \frac{\delta}{2}} \right)^2$$

$$= \tan^2 \left(\frac{\pi}{4} - \frac{\delta}{2} \right),$$

$$\text{or, } \left(\frac{I_{\pi}}{I_{\sigma}} \right)_i = \cot^2 \left(\frac{\pi}{4} + \frac{\delta}{2} \right), \quad (4)$$

where the subscript "i" refers to inflected light.

Equation (6) gives the polarization ratio for an inflection angle δ , in the shadow region.

Consider the situation for deflection into the un-shadowed region* at an angle $-\delta$, where $\varphi = \frac{3\pi}{2} - \delta$; replacing δ by $(-\delta)$ and changing the subscript to "d", for deflection,

$$\left(\frac{I_{\pi}}{I_{\sigma}} \right)_d = \cot^2 \left(\frac{\pi}{4} - \frac{\delta}{2} \right) \quad (5)$$

$$= \tan^2 \left(\frac{\pi}{4} + \frac{\delta}{2} \right) = \frac{1}{\cot^2 \left(\frac{\pi}{4} + \frac{\delta}{2} \right)}, \quad (6)$$

there results:

$$\left(\frac{I_{\pi}}{I_{\sigma}} \right)_i = \left(\frac{I_{\sigma}}{I_{\pi}} \right)_d. \quad (7)$$

Thus the polarization ratio at a given inflection angle in the shadow region is just the inverse of the polarization ratio at the same deflection angle in the non-shadow region.

C. Polarization by a Slit

This argument can be extended to yield an approximate treatment for the polarization to be expected from a slit

* In all observations in the un-shadowed region, the original light from the source is excluded.

made up of two sharp edges. For simplicity we will consider the case of normal incidence ($\varphi_0 = \frac{\pi}{2}$).

It has been proved that the intensity ratios for inflected and deflected light are reciprocal, and now it will be shown that the intensity for parallel light inflected at an angle $\mathcal{S}$ is the same as the intensity for perpendicular light deflected at an angle $-\mathcal{S}$, and therefore that no polarization is to be expected for a slit composed of two sharp half planes.

$$\text{From (1):} \quad Z_{\pi} = C \left[\frac{1}{\cos\left(\frac{\varphi+\varphi_0}{2}\right)} - \frac{1}{\cos\left(\frac{\varphi-\varphi_0}{2}\right)} \right]. \quad (8)$$

For inflection at an angle $\mathcal{S}$, $\varphi - \frac{3\pi}{2} = \mathcal{S}$

so that $\varphi = \mathcal{S} + \frac{3\pi}{2}$

$$\text{Thus} \quad \frac{\varphi+\varphi_0}{2} = \frac{\mathcal{S}}{2} + \frac{3\pi}{4} + \frac{\pi}{4} = \frac{\mathcal{S}}{2} + \pi,$$

$$\text{and} \quad \cos \frac{\varphi+\varphi_0}{2} = \cos\left(\frac{\mathcal{S}}{2} + \pi\right) = -\cos \frac{\mathcal{S}}{2};$$

$$\text{also,} \quad \frac{\varphi-\varphi_0}{2} = \frac{\mathcal{S}}{2} + \frac{3\pi}{4} = \frac{\mathcal{S}}{2} + \frac{\pi}{2}$$

$$\text{and} \quad \cos \frac{\varphi-\varphi_0}{2} = \cos\left(\frac{\mathcal{S}}{2} + \frac{\pi}{2}\right) = -\sin \frac{\mathcal{S}}{2}.$$

Therefore

$$(Z_{\pi})_{\parallel} = C \left(\frac{-1}{\cos \frac{\mathcal{S}}{2}} + \frac{1}{\sin \frac{\mathcal{S}}{2}} \right), \quad (9)$$

which represents the amplitude of the light inflected at an angle $\mathcal{S}$ for parallel polarization. To find the amplitude for a deflection angle $(-\mathcal{S})$ for perpendicular polarization, the sign of the first term in (9) is changed (necessary for the τ case) and $\mathcal{S}$ is replaced by $-\mathcal{S}$.

$$\begin{aligned}
\text{Thus, } (Z_{\sigma})_d &= C \left[\frac{1}{\cos(-\frac{\delta}{2})} + \frac{1}{\sin(-\frac{\delta}{2})} \right] \\
&= C \left[\frac{1}{\cos \frac{\delta}{2}} - \frac{1}{\sin \frac{\delta}{2}} \right]
\end{aligned} \tag{10}$$

$$\text{Therefore, from (9) and (10), } (Z_{\sigma})_d = -(Z_{\pi})_i \tag{11}$$

$$\text{and } (I_{\sigma})_d = (I_{\pi})_i \tag{12}$$

It is pertinent to refer to Figure 2, which shows schematically a narrow slit formed of two sharp edges very close to one another, and to consider the polarization intensity ratio which will be observed at the point Q. For each state of polarization, there is some light diffracted from each edge. The σ case is considered first. Depending upon the phase difference between the light from the two edges, there is observed some resultant intensity of light at Q. The phase difference between the two rays from 1 and 2 depends upon the differences in path length and upon a phase difference of 180 degrees (at the slit) between the inflected and deflected rays. (this 180 degree phase difference is indicated by the negative sign in equation (11) above). The amplitude of the disturbance from edge 1 is larger than that from edge 2. Let $Z_1 = K Z_2$, where K is greater than unity. These disturbances are out of phase by some angle α when they arrive at Q, and their net amplitude may be easily calculated.

Now for the π case $Z_2 = K Z_1$, where K is the same as for the σ case, since from equation (9) the π component

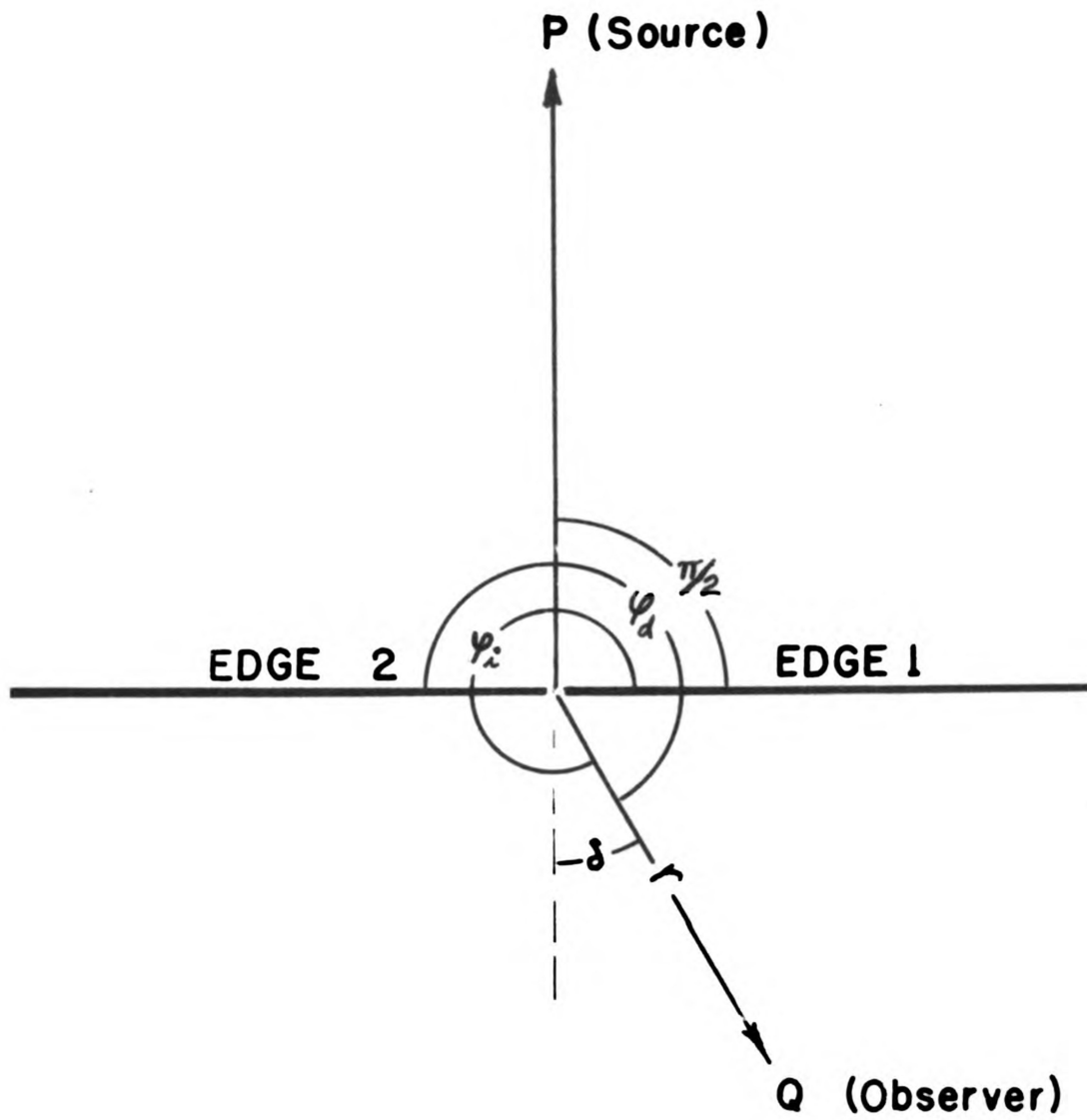


FIG. 2 - SLIT COORDINATE SYSTEM

from 1 is the same as the σ component from 2, and vice versa. Because the path difference is the same for both cases, the phase difference here also is α , so that the net amplitude for the π case is the same as that for the σ case. The π radiation cannot interfere with the σ radiation, therefore it follows that I_π is equal to I_σ .

Thus no polarization is predicted for a "sharp" slit so long as the slit width is large compared with the wavelength of the light and small compared with the distance of the observer from the slit; that is, when the two edges do not interact with one another. This simple treatment considers the two edges to be independent sources.

The same conclusion is indicated, in the more rigorous treatment by Morse and Rubenstein⁶ of a slit made up of mathematical half-planes, for slit widths large compared with the wavelength. It is interesting to note in this connection that for extremely narrow slits the Morse and Rubenstein theory predicts a polarization effect with the ratio I_π/I_σ oscillating as the slit width decreases. In the limiting case of slit width smaller than the wavelength, the theory predicts a strong polarization perpendicular to the edge. However, it will be mentioned later that a "physical" slit, of the type ordinarily used in the laboratory, exhibits strong parallel polarization for small widths.

III. APPARATUS AND METHODOLOGY

A. Characteristics of the Photomultiplier Tube

Since measurements of this phenomenon were made using the electron photomultiplier tube, certain of its characteristics had to be considered in the design of the equipment. These difficulties are discussed in detail by Kessler and Wolfe⁷ and by Weeks⁸, and will be only briefly mentioned here.

The electron photomultiplier tube is a very sensitive light detecting device which responds more or less linearly to the intensity of the incident light. Its two greatest shortcomings are its high "dark current" and its large "fatigue" effect. The term dark current refers to the electron current which flows in the output circuit of the tube when no light falls on the photosensitive surface. The dark current is probably mainly due to the random emission of thermally excited electrons, and manifests itself as a more or less steady D.C. component plus random alternating components which produce a continuous spectrum of "noise" covering the audible range of frequencies. The term fatigue refers to the decrease in sensitivity of the tube with continuing exposure to light and the subsequent slow recovery of sensitivity when the source of light is removed. Another difficulty is the dependence of sensitivity upon accelerating voltage.

The dark current can be minimized in two ways. The first method involves using a light source whose intensity varies periodically, and an amplifier system whose response is high at the frequency of the source intensity variation, but low at all other frequencies. In this way, only those noise frequencies which are nearly the same as the source frequency will be amplified. A second method actually reduces the noise at its source by cooling the tube. Since any reduction of temperature produces some reduction of noise, the temperature used will depend on the particular situation in which the photomultiplier is to be used or the noise which can be tolerated.

The fatigue effect, however, cannot be minimized as effectively. It has been noted⁷ that the rate at which the sensitivity changes is large for high intensities of incident light and small for low incident intensities. Thus the treatment of the fatigue problem requires admitting only the smallest possible amount of light to the phototube. This of course means a lower ratio of signal to noise, and so it is evident that a compromise must be made between the allowable noise level and the amount of fatigue which may be tolerated.

The effect of change in sensitivity with accelerating voltage applied to the tube may be reduced simply by using a well regulated power supply.

Photomultiplier tubes are in general sensitive to the state of polarization of the incident light.⁹ The type which displays this effect the least (RCA 1P28) was used for these measurements.

B. Light Source Requirements

Since the conventional alternating current supply mains have a frequency of 60 cycles per second, it is convenient to make use of the resulting 120 cycle intensity variations in the output of a light source supplied by these mains. One complication involved in using this frequency for a tuned amplifier is that any amplifier operated from a 60 cycle supply will have in its output a certain amount of energy at both 60 and 120 cycles; this energy arises from various sources, one of which is imperfect filtering in the power supply. Thus, if the amplifier is tuned to 120 cycles for the sake of minimizing the noise in a phototube, the amplifier "hum" at 120 cycles will also be amplified.

There are two possible ways to get around this difficulty, both of which were tried and found to be fairly workable. One method requires operation of the amplifier (or at least its first stage) from a battery supply; the other requires using a frequency other than 120 cycles for the intensity variations of the source. The latter can be achieved either by using a D.C. operated light source in conjunction with a chopper or by arranging for a primary supply at a frequency

other than 60 cycles. It happened that there was available in the department a World War I surplus 400 cycle generator having a capacity adequate to operate any available light source. This allowed tuning the amplifier to 800 cycles and practically eliminated the 120 cycle hum in the amplifier.

Any light source produces an output which is only approximately constant, even when operated from a very well regulated power supply. In order to avoid errors occurring from these random fluctuations, a comparator measurement system was used such that light directly from the source was compared with that observed in the diffraction pattern.

Since it is necessary in these measurements that the light source be unpolarized, there is need to determine whether or not this condition is satisfied.

In order to obtain the maximum possible light intensity in the diffraction pattern, a high-powered (750 Watt) mercury arc was used as a source. It was found later that a lower powered arc (100 Watts) of the high pressure type served just as well as the larger arc.

C. The Comparator Detector

Since the random variation of intensity to be expected from the light source had to be dealt with, a comparison detector was used. In this system, two photomultiplier tubes are used. One "looks" directly at the source; the other looks at the light diffracted from the straight edge. It is desired

to measure the change in intensity of the diffracted light as the state of polarization of the incident light is changed from parallel to perpendicular with respect to the edge. In order to measure the ratio of the intensities observed by the latter tube, a tuned two channel amplifier was used. Each channel is tuned by a degenerative twin "T" filter. One of the channels contains a calibrated attenuator. Figure 3 is a block diagram of the circuit.

If the two phototubes are illuminated with light of the proper intensity to produce equal voltages at the grids of the phase balancing tubes, and the phasing adjustments are made so that the two voltages are 180 degrees out of phase, the output voltage at the commonly connected plates will be essentially zero. If now the intensity of the light falling on the upper tube is allowed to increase to, say, twice the original intensity, the output voltage will be large. Then if the signal in the upper channel is attenuated to half its new value, the grid voltages at the phase balancer will be equal again, and the output voltage on the plate will be essentially zero.

The ratio of the two voltages (from the upper tube) is determined by the two settings of the attenuator for exact balance. Since the signal level in the lower amplifier is constant, and the signal level in the upper amplifier is constant when the attenuator is set for balance, the only part of the circuit except for the attenuator which could

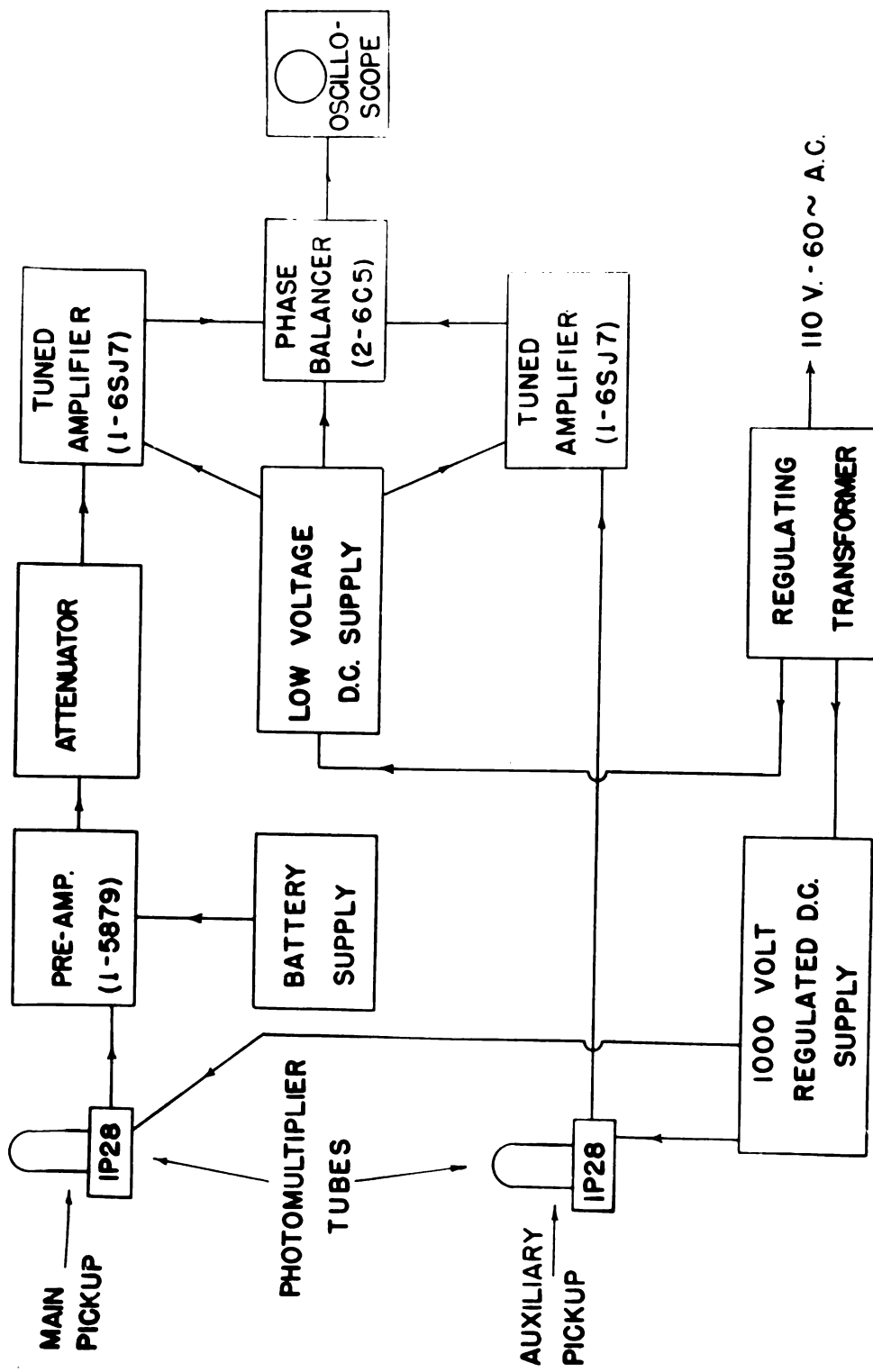


FIG.3 - BLOCK DIAGRAM OF ELECTRONIC EQUIPMENT

affect the accuracy of the ratio is the pre-amplifier. As long as the pre-amplifier is operated linearly, it will not affect the results. In order to insure that this condition is satisfied, the output voltage of the comparator is observed on an oscilloscope. Whenever the signal is large enough to produce distortion in the pre-amplifier, there appears on the oscilloscope the harmonic content of the pre-amplifier output, which cannot be balanced out. The light intensity must then be reduced to eliminate the distortion. In practice, this is accomplished by inserting a neutral density filter into the optical path ahead of the polarizer.

Figure 4 is the circuit diagram of the pre-amplifier. All voltages are battery supplied in order to reduce hum. The type 5879 tube was chosen for its low microphonic response.

Figure 5 is the circuit diagram of the two channel amplifier. It should be noted that in order to obtain cancellation it is necessary to have the voltages at the two output tube grids equal and out of phase. This is accomplished by having one more stage of amplification in one arm of the system than in the other. The extra stage is the pre-amplifier. Precise phase cancellation is obtained by adjusting one or both of the phase control rheostats.

Figure 6 contains diagrams of the high voltage and low voltage power supplies. The high voltage supply incorporates a 6Y6 series regulator controlled by a 6SJ7 amplifier, which is in turn biased by three VR-150 gaseous regulator tubes.

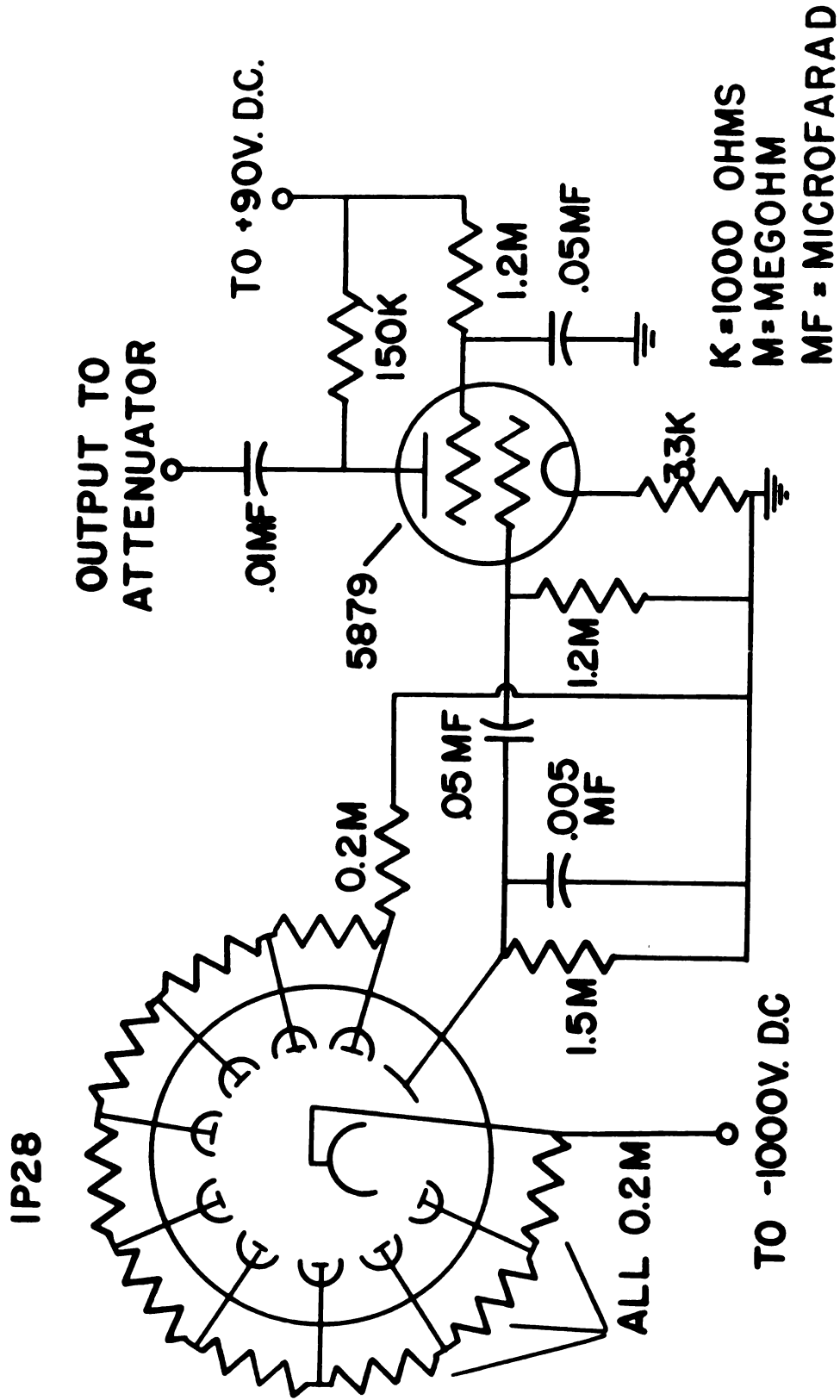


FIG. 4 - CIRCUIT DIAGRAM OF PICKUP UNIT.



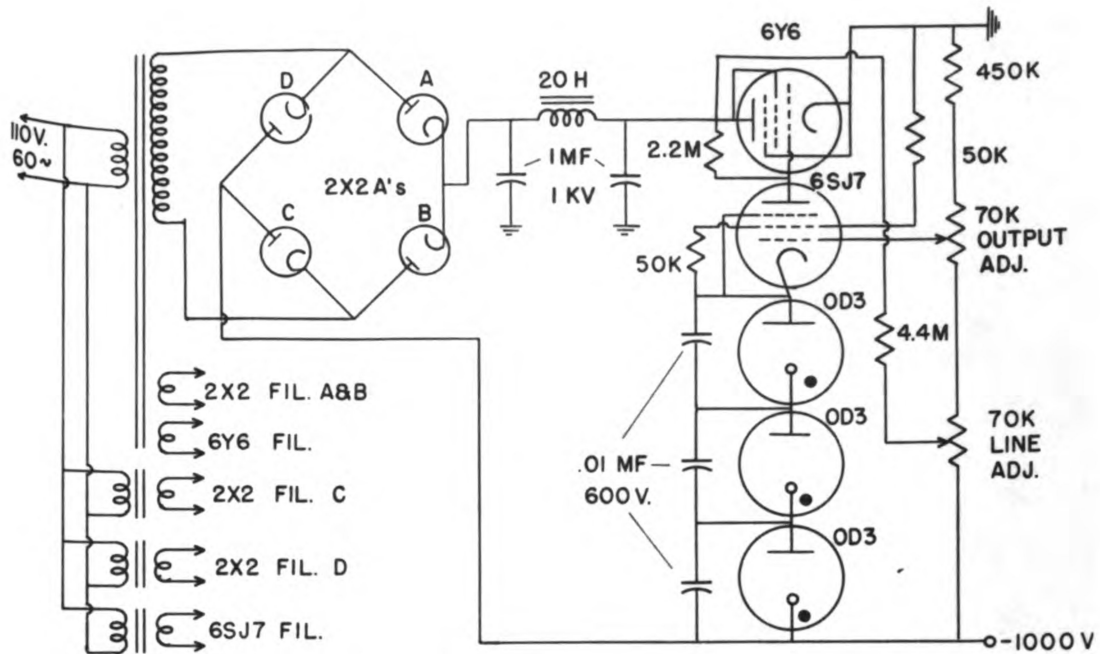


FIG. 6a. HIGH VOLTAGE POWER SUPPLY

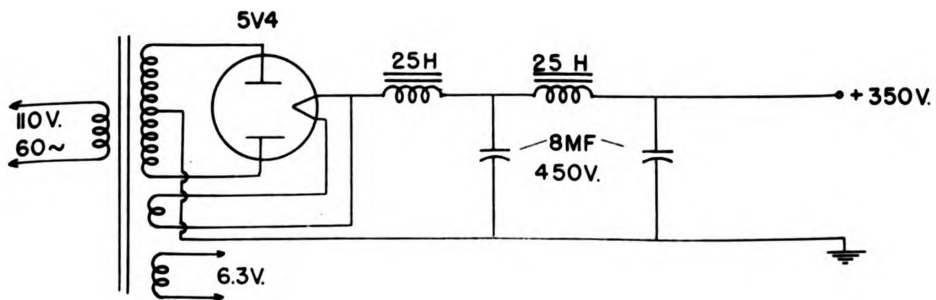


FIG. 6b. LOW VOLTAGE POWER SUPPLY

D. Photomultiplier Cooling System

It has been mentioned previously that the noise output of the photomultiplier may be reduced by lowering its temperature. Attempts were made to cool the tube using solid carbon dioxide. In the photograph (Figure 7) of the optical system it is possible to see the polystyrene foam ("styro-foam") box surrounding the main pickup. Solid carbon dioxide was placed inside the box, and the box was covered with a styro-foam lid. The thermal insulation properties of the box were excellent. However, it was not found possible to sufficiently reduce the frost formation at the aperture. After a period of half an hour the frost would begin building up on the aperture thereby increasing the pickup of stray light.

For this reason the system was abandoned, despite the increase in signal to noise ratio effected by the cooling.

E. Optical Equipment

There will be two optical systems discussed here. The first, which incorporated two lenses, was used for all observations except the last set shown in Figure 13b. This last set of observations was made on a lens-free system.

The early optical set up is shown diagrammatically in Figure 8. Light from the 750 Watt Hanovia Mercury vapor lamp was passed through the slit, the filter for the mercury green line, the variable neutral density filter, the Polaroid polarizer, and thence through the 12.5 cm. lens to the diffracting

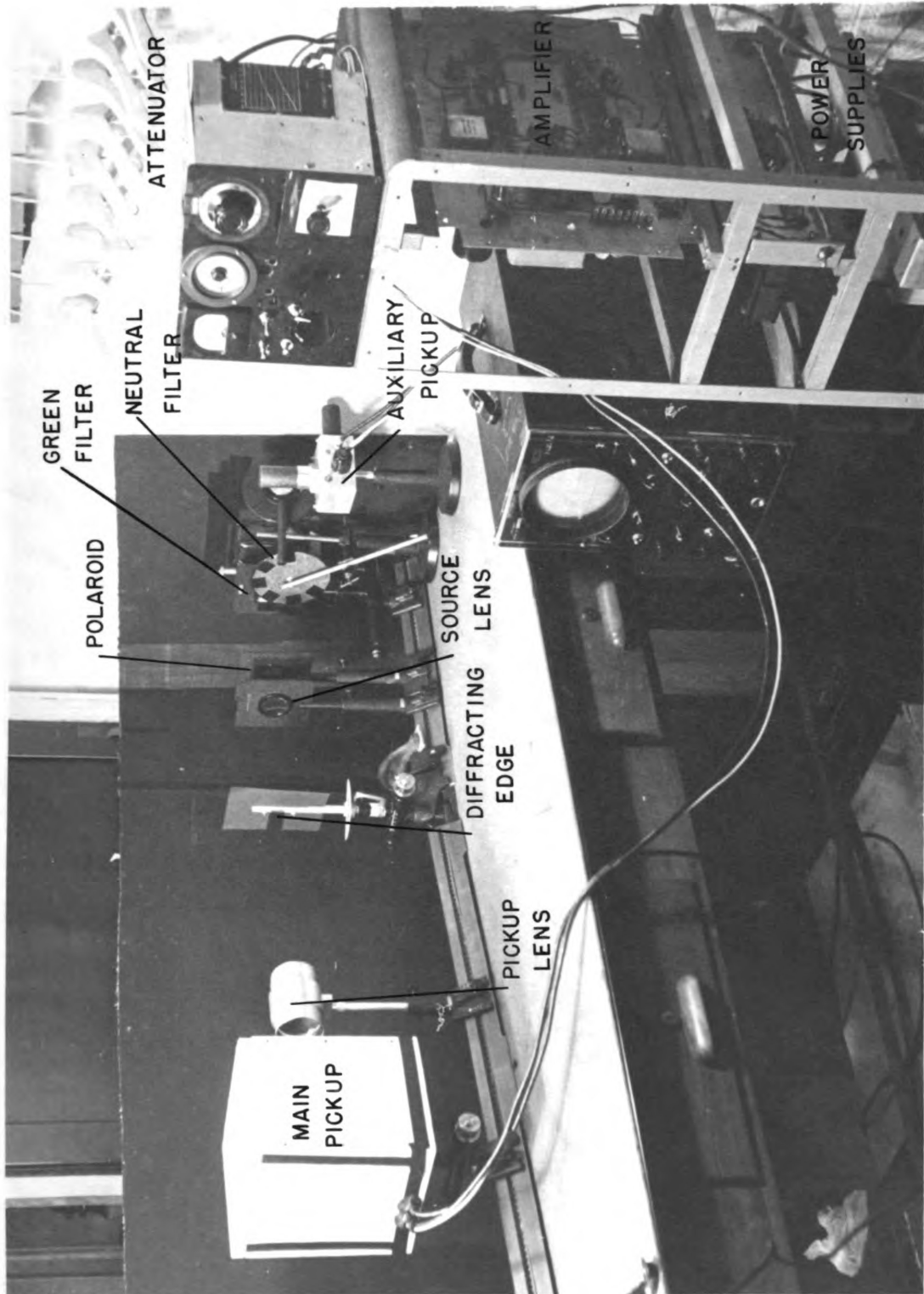


FIG. 7. PHOTOGRAPH OF OPTICAL AND ELECTRONIC EQUIPMENT

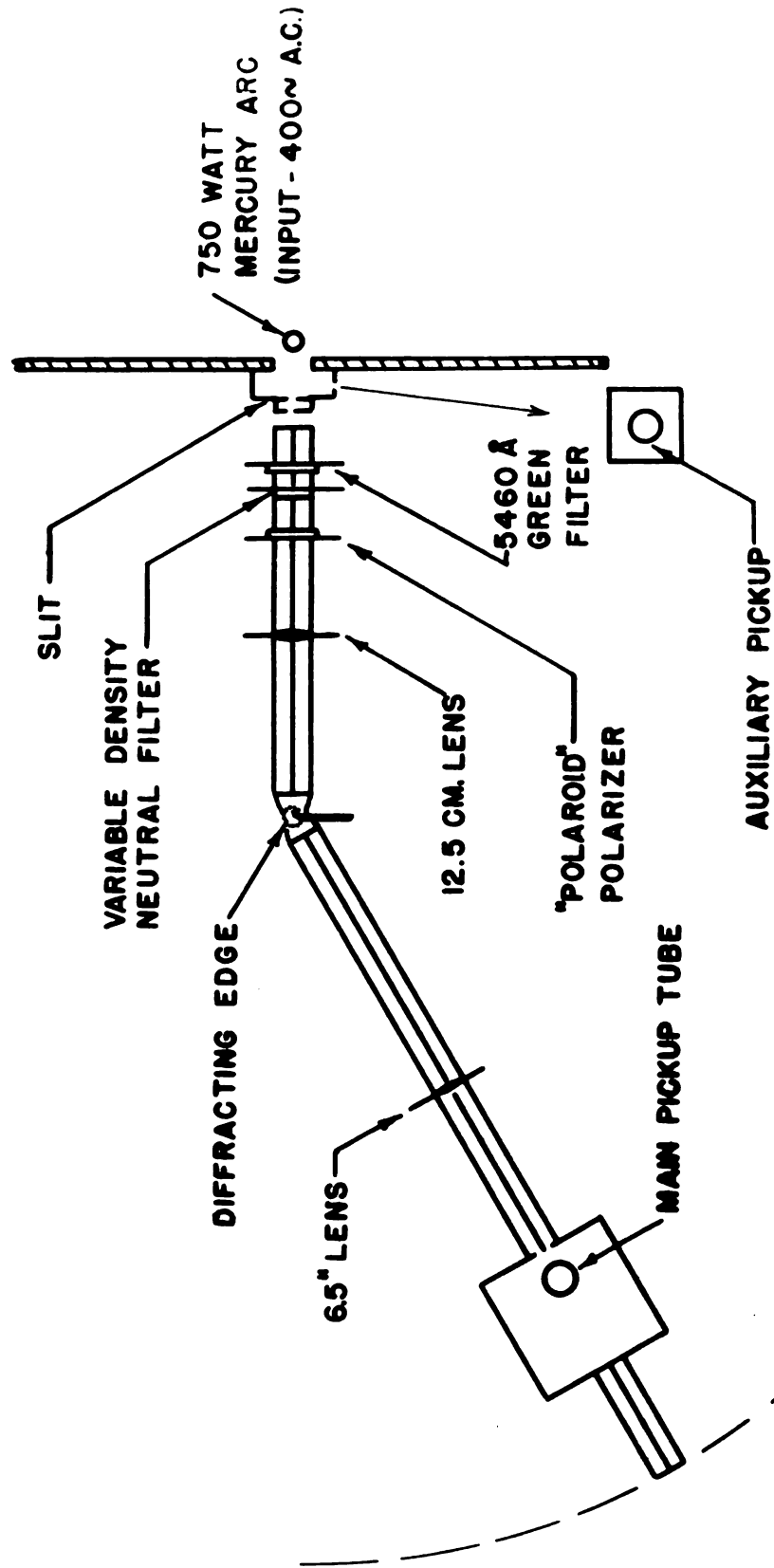


FIG. 8. OPTICAL EQUIPMENT LAYOUT

edge. The slit was imaged on the diffracting edge. Light diffracted from the edge was focused on the photomultiplier tube by means of the 6.5 inch lens.

Early attempts were made to use a Nicol prism as a polarizer, but it was discarded due to its small aperture and the internal reflections which caused the intensity of the light striking the edge to vary as the Nicol was rotated. An attempt was made to use a Wollaston prism as a polarizer, but this had to be abandoned when it was found that the prism available was not exactly symmetrical, with the result that the two beams were deviated at different angles from the axis of the optical system and caused a variation (at the razor edge) of intensity with polarization direction. The Polaroid was used because of its large aperture and freedom from intensity variations with changing polarization. It was found necessary to use monochromatic light, since the particular type of polaroid used was a rather poor polarizer in the violet region but polarized very well in the green region of the spectrum. It should be noted that the polarization ratio is independent of wavelength according to Sommerfeld's theory, and that monochromatic light was used here only to insure complete polarization.

The neutral density filter was used to reduce the intensity of the light observed at small diffraction angles in order to avoid overloading the amplifiers.

The 12.5 cm. lens was used to increase the intensity of light incident on the edge and thus minimize the effect of stray scattered light, which tended to mask the polarization effect. The 6.5 inch lens was used to eliminate as much as possible of the stray light scattered into the photomultiplier from unwanted sources. In practice, the edge was imaged on the phototube, and the phototube aperture was restricted to the dimensions of this image.

The diffracting edge finally used was simply an ordinary safety razor blade. Microscopic examination of several brands indicated that Gillette Blue blades were most consistently sharp. Under the microscope it was possible to see the grooves made by the operation of grinding the edge. On a well sharpened edge the final honing operation removes all these grinding grooves in the vicinity of the edge. The completeness of this final honing operation was used as a criterion in selecting blades to be used.

After examination under a 400 power microscope, the blades were silver coated by evaporation under a high vacuum. The thickness of the coating was approximately 400 Angstroms, as judged by the opacity of the coat on a glass microscope slide. To illustrate the importance of the shape of the edge, a few blades were modified by blunting their edges. This was accomplished by drawing the blades once very lightly over an extremely fine whetstone, previous to the silvering operation.

In order to minimize the amount of stray light reaching the phototube, light shields were employed. These paper baffles are not shown in the photograph of the optical system.

F. Operation of the System

The attenuator in the upper channel of the amplifier is set for minimum attenuation, the polarizer set for parallel polarization, and the variable slit on the auxiliary pickup tube adjusted to attain a balance at the phase balancer. If the main pickup tube is in the geometrical shadow region. the intensity of the light falling on it will increase when the polarizer is rotated to produce polarization perpendicular to the edge. In order to again obtain a balance, it is necessary to attenuate the signal from the main pickup tube. When the signal is attenuated by the exact amount necessary to obtain a balance, the attenuator setting is observed. Reference to the attenuator calibration chart gives the output to input voltage ratio. This ratio is interpreted as the intensity ratio of the weaker component to the stronger. In the geometrical shadow region this is the ratio I_{π}/I_{σ} . When this process is carried out for various deviation angles, it is then possible to plot the polarization ratio as a function of the inflection angle.

As mentioned before, it is necessary to keep the light level low enough to avoid distortion in the amplifiers. When distortion appears, the intensity may be reduced by inserting the appropriate neutral filter into the main optical path.

IV. EXPERIMENTAL OBSERVATIONS

In addition to the quantitative data there are included hereunder several items which represent observations of a qualitative nature but which are nevertheless pertinent to the investigation.

These are the phenomena which were measured:

1. The ratio I_{π}/I_{σ} for sharp, silvered razor edges, for inflection angles up to 60 degrees, for incidence angles of 90, 75, and 60 degrees, respectively. See Figures 9a, 10a, 11a, below.
2. The same as above for blunted, silvered edges. See Figures 9b, 10b, 11b.
3. The ratio I_{σ}/I_{π} for a sharp, silvered edge, for deflection angles up to 60 degrees in the unshadowed region. See Figure 12a.
4. The ratio I_{π}/I_{σ} for a slit formed of two sharp, silvered edges, with a slit separation of 0.16 mm. with light normally incident. See Figure 13a.
5. The ratio I_{π}/I_{σ} for a sharp, silvered edge in the shadow region, using an optical system with no lenses, and using a 100 Watt, concentrated, high-pressure mercury arc for a source. See Figure 13b.

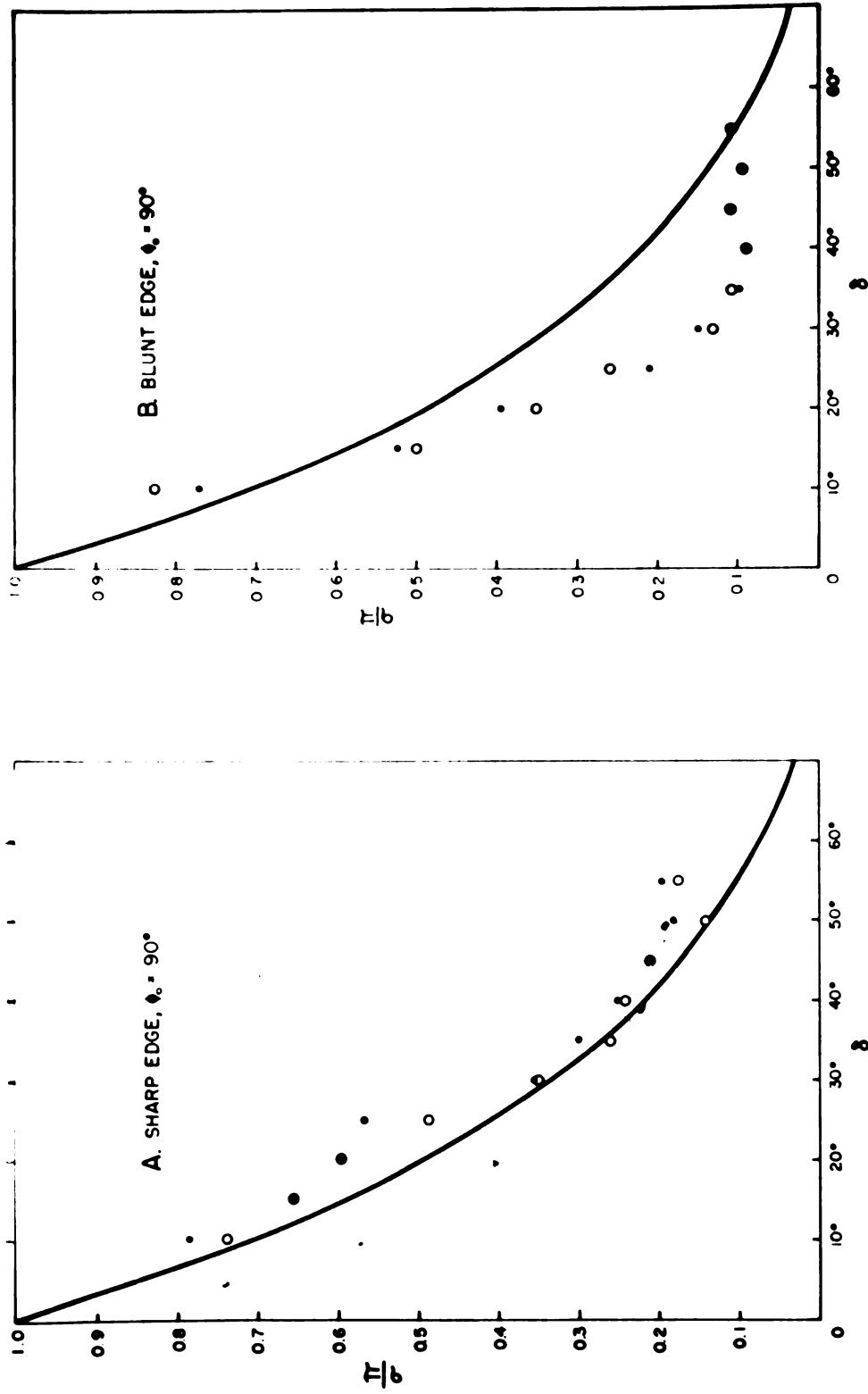


FIG. 9. PLOT OF INTENSITY RATIO VS. INFLECTION ANGLE. SOLID CURVE CALCULATED FROM EQ.(3)
 (*, o INDICATE CONSECUTIVE OBSERVATIONS)

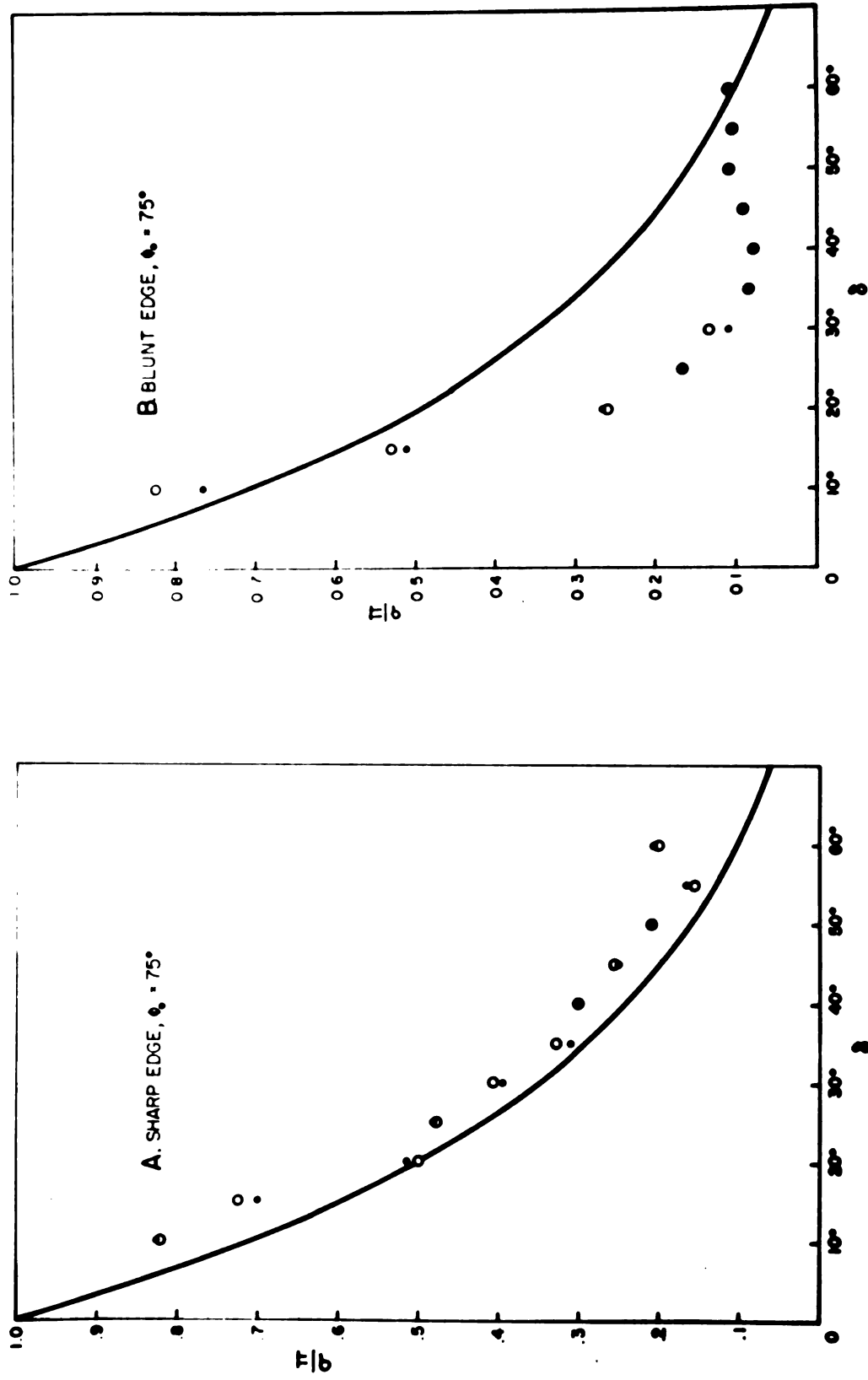


FIG. 10. PLOT OF INTENSITY RATIO VS. INFLECTION ANGLE. SOLID CURVE CALCULATED FROM EQ.(3)

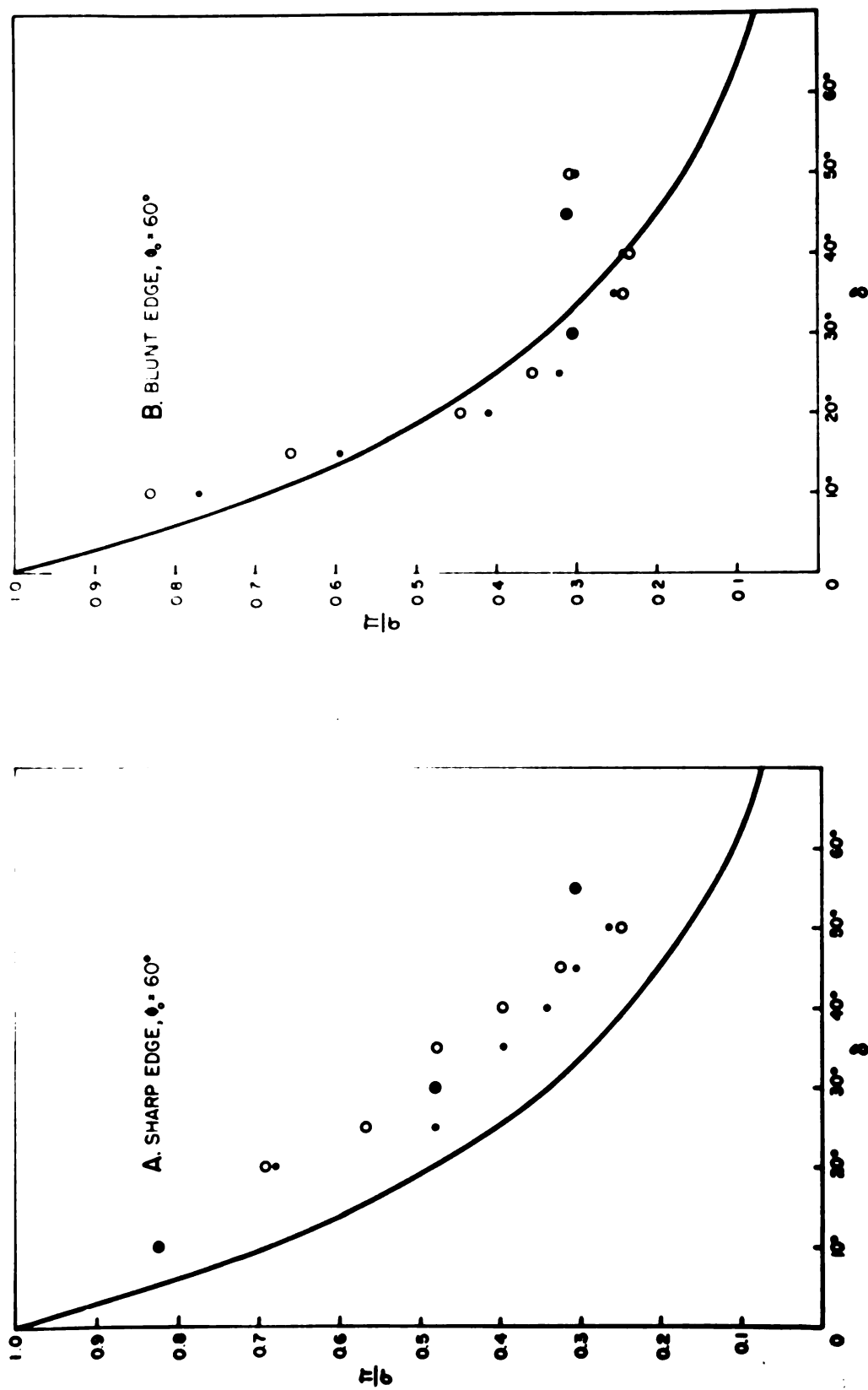


FIG. 11. PLOT OF INTENSITY RATIO VS. INFLECTION ANGLE. SOLID CURVE CALCULATED FROM EQ. (3)

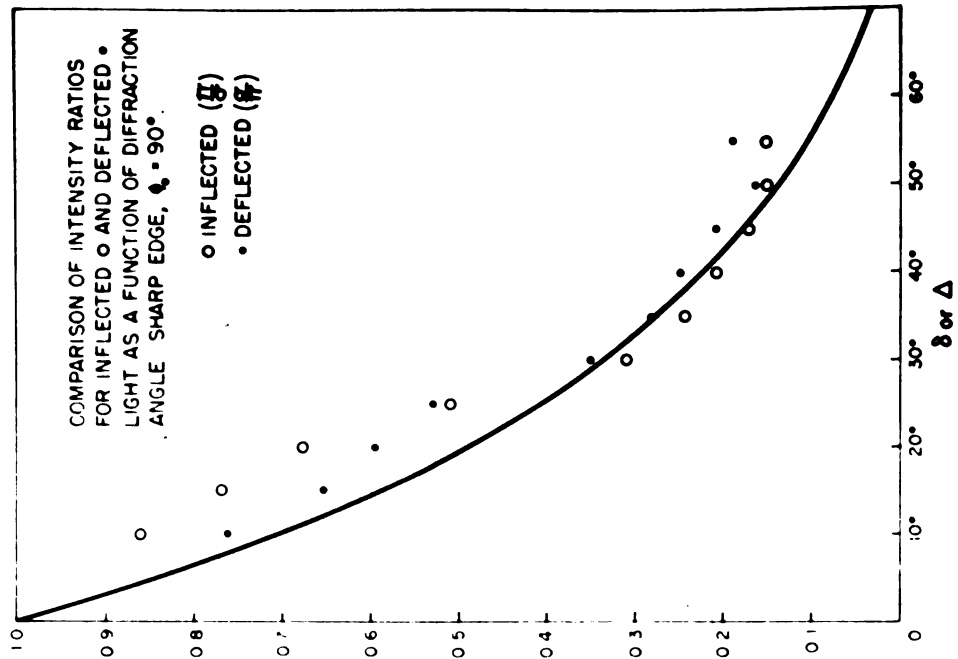


FIG. 12 b

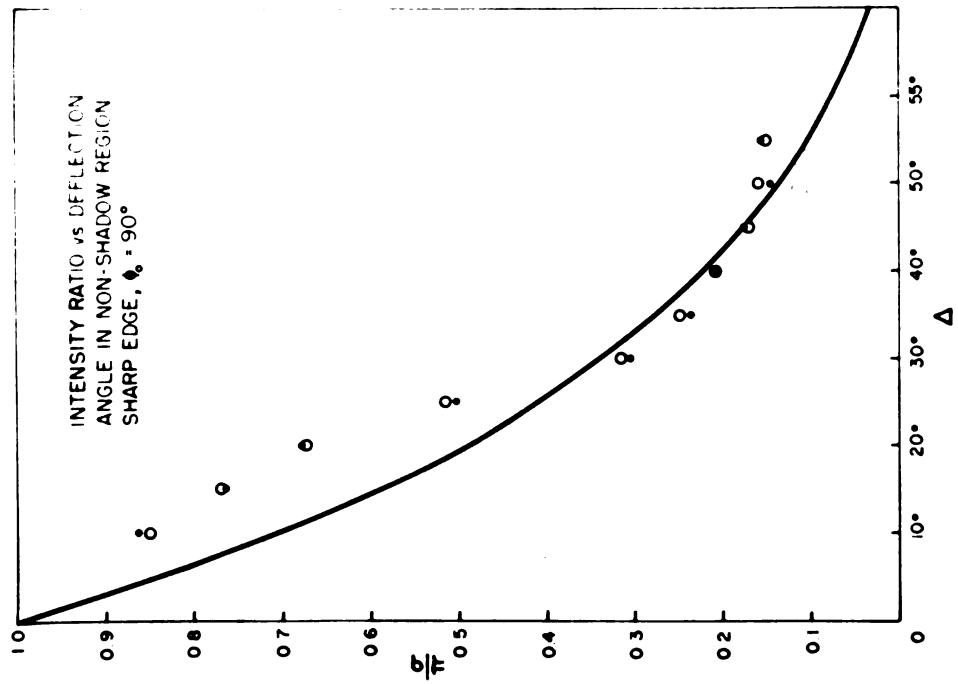


FIG. 12 a

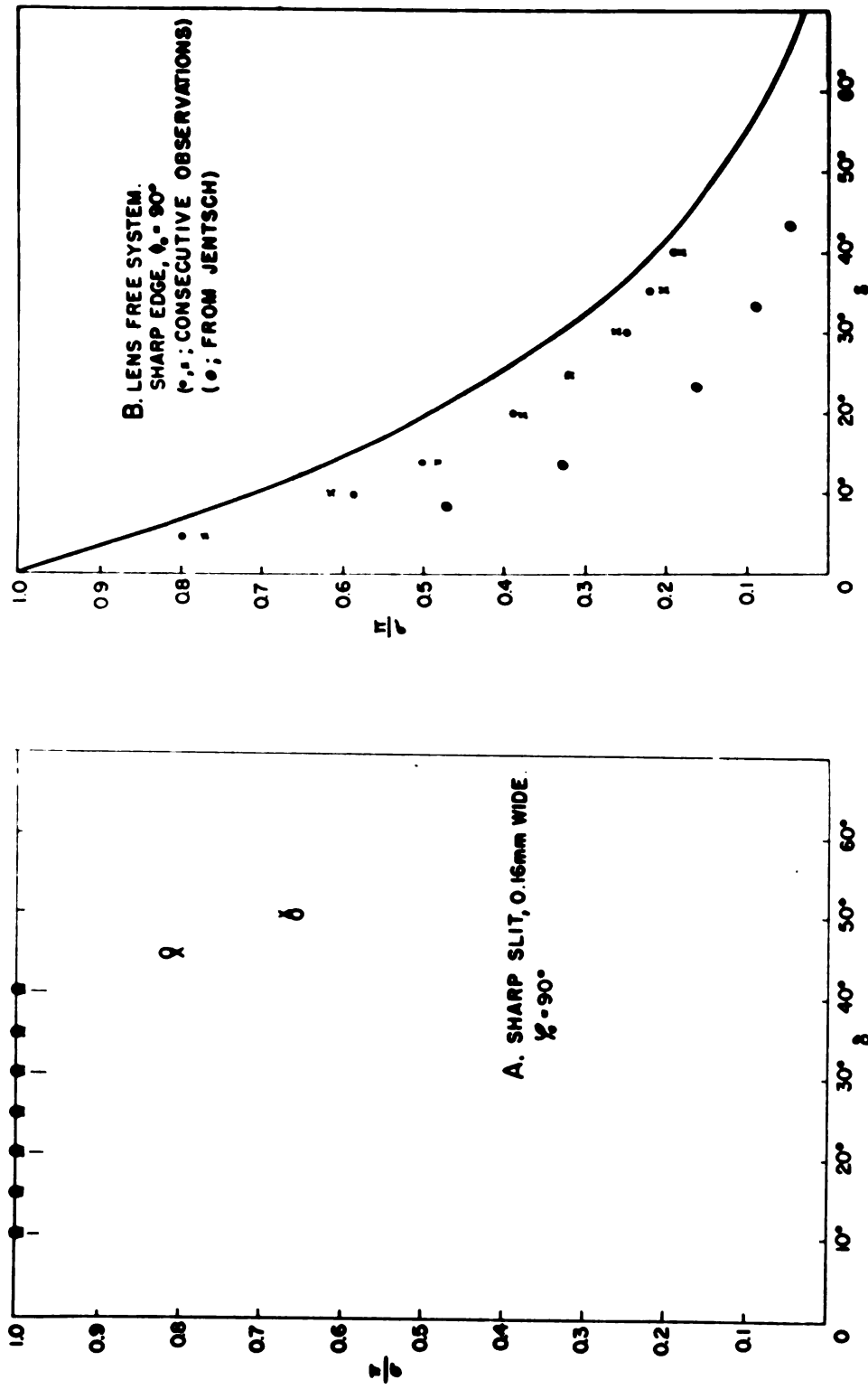


FIG.13 PLOT OF INTENSITY RATIO VS. INFLECTION ANGLE.

In addition to these measured phenomena, the following information was obtained:

6. While attempting to control the light flux into the main pickup tube by means of an adjustable slit, it was observed that when the slit was closed down it acted as a polarizing element. As the slit width was decreased, the degree of polarization was increased, and the polarization was always parallel to the slit.

7. In the process of attempting to track down the variation caused by the slit polarization, the state of polarization of the light from the mercury arc was investigated. Within the limits of the accuracy of the instrument, there was found to be no polarization of the source.

8. The degree of polarization produced in the incident light by the Polaroid was measured and found to be sufficiently perfect for the purposes of this investigation when the light was filtered to pass only the Mercury green line. The ratio of the uncrossed to crossed transmission of a pair of such Polaroids was found to be greater than 100 to 1.

9. A small amount of dust or smoke in the air near the diffracting edge will produce erroneous results, as was observed when an ash tray containing a smouldering cigarette was inadvertently placed near the diffracting edge. When such a high concentration of particles exists in the air near the diffracting edge, the amount of light scattered by these particles is much greater than the light diffracted from the

razor edge, thus masking the polarization effect or even obliterating it.

10. One set of blades was unintentionally silvered in a poor vacuum, with the result that the silvered surface took on a bluish color. The discoloration may have been due to some chemical reaction between the evaporated silver and the gases in the evaporator, or to a reaction involving Molybdenum unintentionally evaporated from the heating element. When measurements were made of the polarization ratio in the shadow region, it was found to be just the inverse ratio (qualitatively speaking) of that which is normally observed. That is, the parallel component was stronger than the perpendicular component. Examination of the edges under a 400 power microscope showed an aggregation of crystalline lumps on the surface.

11. In general it was found that after exposure to the air for a day or so the edges underwent changes which tended to reduce the intensity of the overall diffraction pattern. This was true for silvered as well as unsilvered steel edges. As a result, all observations included in this report were made on freshly silvered blades. The effect, however, might be considered as a method for the determination of relative sharpness of razor blades.

12. Some measurements were made of the change of intensity with distance for constant incidence and diffraction angles, and constant state of polarization. The intensity

was measured at distances of 40 and 80 cm. from the edge. For the system containing lenses, the intensity ratio observed varied between $1/3$ and $1/4$, while for the lens-free system the value observed was between $1/2$ and $3/8$. In order to make this observation on the system containing lenses, it was necessary to remove the 6.5 inch lens, since at the shorter distance it was not possible to focus the edge on the pickup tube. For both measurements the length of the pickup tube aperture was one inch, while the length of the blade was $1\frac{1}{4}$ inches and that of the source 2 inches.

V. DATA ANALYSIS AND CONCLUSIONS

A. Sources of Error

It is expected that all the observations on the system containing lenses yielded intensity ratios which were too high. There are three reasons for this. They are: 1. Effective source broadening due to the source lens; 2. Effective pickup aperture broadening due to the pickup lens; and 3. Masking of the diffracted light by stray scattered light.

The source lens has the effect of broadening the source, as may be seen in Figure 14. The angles recorded for incidence

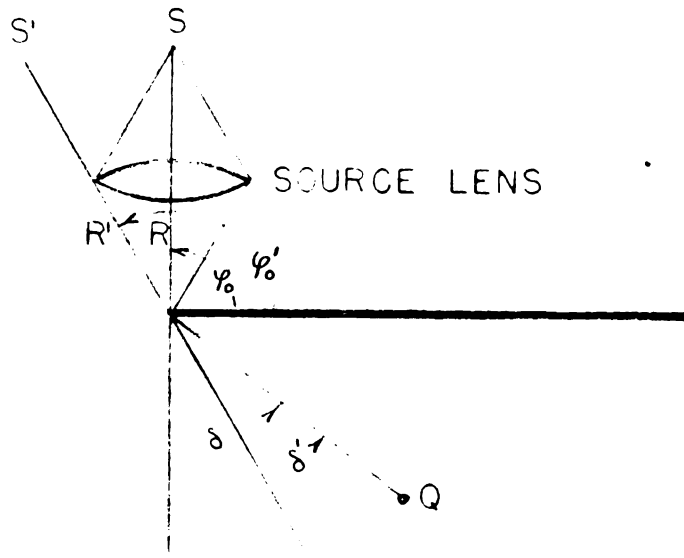


Fig. 14 - Source broadening effect of source lens.

and inflection are φ_0 and δ respectively. These angles are appropriate only for axial rays from S. For oblique rays,

as for example R' , the inflection angle should be measured from the extension of R' . For the same observer's position, the inflection angle would be a smaller angle, δ' . Since the light from R' has been inflected through a smaller angle (δ') than the light from R , the intensity of both its polarization components will be larger and more nearly equal than the intensities of the two polarization components from R . In other words the light from R' is more intense and less highly polarized than the light from R ; therefore the observed polarization ratio will be higher than would be appropriate for light incident only along R .

The pickup lens adds to this effect by collecting light from a large number of inflection angles. Here again, the

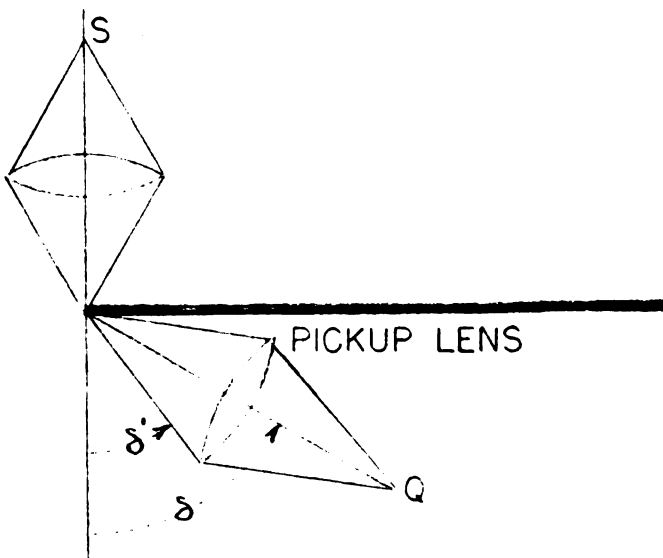


Fig. 15 - Pickup broadening effect by pickup lens.

highest intensity light is light which is less highly polarized than would be appropriate for the measured inflection angle δ . On the scales used to plot the intensity ratios, a large value of the intensity ratio corresponds to a low degree of polarization. Conversely, a low ratio corresponds to a high degree of polarization. Thus, on these scales, the observed values are probably too high, for the reasons just mentioned.

Both of these effects are partially nullified by the light from the other side of the lens, and therefore the effects should be most noticeable for small inflection angles.

When the ratio is observed at large inflection angles, the effect of the stray scattered light becomes important. For example, let us say the intensity ratio I_{π}/I_{σ} of the light actually coming from the edge to the pickup is 1 to 4, or $I_{\pi}/I_{\sigma} = 0.25$. Suppose the stray light is twice as strong as the π component. What the pickup would see would be a ratio of 2 to 4, or $I_{\pi}/I_{\sigma} = 0.5$. Thus for increasing values of the inflection angles the observed ratios are increasingly too large.

Another source of error was the frequency instability of the 800 cycle source. Since the phase responses of the two amplifiers cannot be made identical, when the frequency of the source changes it is no longer possible to reach an exact cancellation. That is, the signals at the grids of the phase balancer tubes are no longer exactly 180° out of phase and therefore complete cancellation cannot be effected, without readjusting the phase controls.

In all the measurements, the photomultiplier noise was present and made it difficult to determine the exact position of balance. In addition to the noise, the fatigue effect was always present.

The latter two effects are mainly responsible for the variation of the observed values from one trial to the next. This variation is of the order of 0.05 on the scales used to plot the ratios.

B. Discussion of results

1. Sharp edge (Figures 9a, 10a, 11a): The results for inflected light for incidence angles of 90° and 75° appear to agree with the Sommerfeld theoretical curves, but must be interpreted as being too high for the reasons mentioned above. For 60° incidence the intensity of both components was low. The large scatter of the points is attributed to the large noise level, and the fact that they are higher than the theoretical curve is attributed to the masking effect of the scattered light.

2. Blunt edge (Figures 9b, 10b, 11b): Since the exact shape of the edge is not known, these curves are mainly valuable for showing that a variation in the shape does drastically change the polarization effect. The fact that the points start to swing up at large inflection angles is probably due to the masking effect of scattered light.

3. Sharp edge in deflected light (Figure 11c): The ratios observed in the non-shadow region (i.e. for deflected light) show good agreement with those for the shadow region (Figure 9a), as is shown in Figure 12b, on which the two sets of points are plotted together. It should be noted here that the ratios plotted in the non-shadow region are I_{σ}/I_{π} , so that in Figure 12b, the circles are ratios of I_{π}/I_{σ} , while the dots are I_{σ}/I_{π} . The observations essentially confirm the predictions that the ratios for inflected and deflected light would be the reciprocals of one another.

4. Sharp slit (Figure 13a): Within the limits of the accuracy of the system, the light diffracted by a sharp edged slit is shown to be unpolarized. The data agree with the predictions of the approximate theory for the slit, and are complementary to the data obtained for single edges in the shadowed and unshadowed regions. The fact that the ratio I_{π}/I_{σ} drops off at large angles is attributed to the fact that the near edge (which contributes mainly perpendicularly polarized light) begins to shield the far edge (which contributes mainly parallel polarized light), and that therefore the parallel component suddenly begins to decrease more rapidly than the perpendicular component.

5. Physical slit: The qualitative observation of polarization by a slit having flat jaws may perhaps be explained by the fact that the light traveling through the slit is multiply

reflected from its faces. As the slit becomes narrower, the number of reflections increases, and therefore the degree of polarization increases. From this argument, the direction of polarization would be along the long dimension of the slit, which is the same direction as the observed polarization.

6. Sharp edge polarization ratio, lens-free system

(Figure 13b): The observed ratio was always less than the theoretical value. There was somewhat less variation in the observed values than in all the earlier measurements, which may be due to the fact that with practice it becomes possible to perform the necessary manipulations more quickly, and therefore to reduce the variation caused by photomultiplier tube fatigue. In addition, the amount of scattered light entering the pickup was reduced by placing the equipment so that the nearest wall was some thirty feet distant. In the earlier measurements, the nearest wall (painted flat black) was only two feet from the equipment.

7. Change of intensity with distance: These observations were difficult to reproduce, and so the results are interpreted in a more or less qualitative manner. Apparently in the lens-free system, light is radiated from the edge somewhat in the form of cylindrical waves, since the intensity varies approximately as $1/R$.

It would be appropriate to make these measurements with a pickup aperture whose length is much smaller than the

length of the edge. However, it is believed that the only requirements for observing the change of intensity with distance are that the length of the pickup be less than the length of the edge, which in turn must be less than the length of the source.

C. Comparison with Previous Work

Observations of the amplitude polarization ratios were made in 1927 by Jentsch³. Earlier observations were made by Gouy and Wien, but it is believed that the later measurements of Jentsch are probably more of interest for our purposes.

Jentsch's observations were made on a modified prism spectrometer. A polychromatic Osram tungsten point light was used as a light source. Light from the source was collimated, after which it passed through a Nicol prism oriented at an angle of 45° to the vertical. From the polarizer, the light went to the diffracting edge (a steel razor blade) which was mounted upon the prism table with its edge vertical. The diffracted light from the edge passed through another Nicol prism, thence through the telescope, which was focused upon the diffracting edge.

The plane of polarization of the diffracted light was observed to be rotated, due to the inequality of the parallel and perpendicular diffraction components, and the rotation was recorded as a function of the diffraction angle.

From the amount by which the plane of polarization was rotated, Jentsch calculated the amplitude ratios of the two polarization components.

The results of this investigation were originally compared with a plot of Jentsch's results in the Handbuch der Physik¹¹. This plot showed one of Jentsch's experimental values to be larger than Sommerfeld's theoretical predictions, and seemed to indicate a major discrepancy between our results and Jentsch's. However, after reviewing Jentsch's own paper³ it was found that his values were all less than Sommerfeld's prediction.

For comparison purposes, a plot of the intensity ratios calculated from Jentsch's amplitude ratios is included in Figure 13b. The fact that his ratios are smaller is possibly due to the lower conductivity of the steel blades which he used.

D. Suggestions for Improving the Equipment

The attenuator used has two controls--a ten position switch for coarse adjustment and a potentiometer for fine adjustment. It would be easier to determine the exact situation of balance if a completely continuous type attenuator were used. A possible substitute is the "Helipot" 1 megohm type AZ ten turn helical potentiometer.

A possible method for cooling the photomultiplier tube would be to immerse it in liquid nitrogen in a Dewar flask.

It would be necessary to make a small transparent window in the flask by removing the evaporated metal. There probably would be little frost formation if the "window" were small enough. However, it is not known whether the glass to metal seals on the photomultiplier tube would withstand such treatment.

The fatigue effect can be eliminated by using a method of measurement¹⁰ in which the comparison light signal is fed to the same pickup as the one which "looks" at the diffraction pattern by means of a chopper system. In this system, the pickup sees the light from the two sources during alternate time intervals. Since the fatigue affects both signals in the same way, it will not contribute to the error of the measurement.

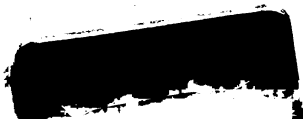
E. Summary of Conclusions

The experimental results which have been obtained agree in general with the predictions of Sommerfeld's theory and the approximate slit theory. Sommerfeld's theoretical work is based on the assumptions of perfect conductivity and infinitesimal thickness of the diffracting edge. At present there is no way to alter the theory to take these factors into account. In view of this fact, the observed discrepancies seem reasonable, since the diffracting edges, being real edges, suffer from some of the imperfections of reality.

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