Journal of the

OPTICAL SOCIETY *of* AMERICA

VOLUME 23 MARCH, 1933 NUMBER 3

Standing Light Waves; Repetition of an Experiment by Wiener, Using a Photoelectric Probe Surface

HERBERT E. IVES AND THORNTON C. FRY, *Bell Telephone Laboratories, New York, N. Y.*

(Received January 20, 1933)

A CLASSICAL experiment in optics was performed by Wiener[1] in 1890. By placing a thin photographic sensitive film at a small angle with a metal mirror, he demonstrated the existence of standing waves by getting traces of the loops of the waves in the developed film. Later a similar experiment was performed by Drude and Nernst, substituting a thin fluorescent surface as the probe. In these experiments the action of the light was found to be associated with the electric vector.

In recent studies which we have been making, in order to evaluate the influence of purely optical conditions on the photoelectric effect in thin films of alkali metals, we have been led to the view that the photoelectric emission from such films is directly correlated with the amount of energy absorbed by the films. According to this view, for which considerable support has already been given,[2] the peculiarities shown under polarized light are natural consequences of the fact, shown by detailed analysis of the optical factors, that the energy absorbed by the thin films deviates materially in amount from that which would be the case were the bulk absorption of the irradiated surface the significant factor, as had been previously generally assumed. The absorption in the film we arrive at by computation from the optical constants of the metal underlying the film, and of the film itself. The methods of computation prove to be the equivalent of determining the interference pattern above the metallic base, alone, and then regarding the alkali metal film as being immersed in this pattern. Looked at in this way the thin film of alkali metal plays the same rôle as the probe surface used by Wiener, Drude and Nernst, except that it is in contact with the reflecting surface instead of being at an angle to it. The present study was undertaken as part of the experimental support which was sought for our theory of photoelectric action, and had for its object lifting the sensitive film up to different positions above the reflecting metal surface, to find out whether the photoelectric current followed the very considerable alterations in the energy density which computations indicate. The experiment thus inspired is obviously a variant on the experiment of Wiener, and warrants the use of the title chosen.

[1] See Wood's *Optics*, 2nd Ed., p. 175 for a general account of these and other stationary light wave experiments.

[2] Ives, *The Vectorial Photoelectric Effect in Thin Films of Alkali Metals*, Phys. Rev. **38**, 1209 (1931); Ives and Briggs, *The Photoelectric Effect from Thin Films of Alkali Metal on Silver*, Phys. Rev. **38**, 1477 (1931); Ives and Briggs, *The Depth of Origin of Photoelectrons*, Phys. Rev. **40**, 802 (1932).

By referring to Fig. 1, the nature of the experiment will be clearly seen. At the bottom of the figure is represented the underlying metal, for instance platinum, upon which to the left is shown a thin film of alkali metal, which is assumed, in accordance with several lines of evidence, to be only an atom or two in thickness. To the left is shown the relative energy density, as a function of distance above the surface, in two beams of light, incident at an angle of 60°

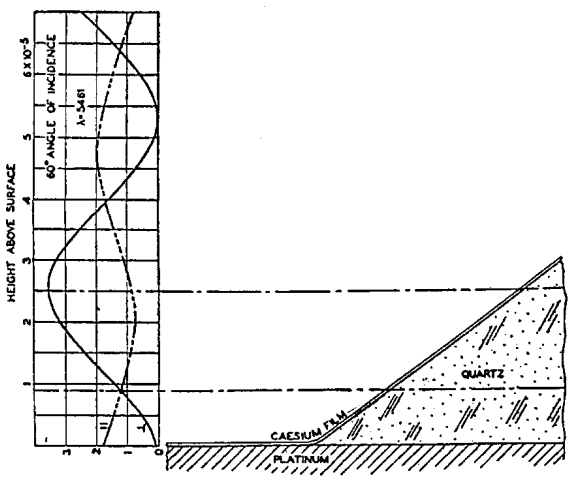

FIG. 1. Diagrammatic representation of experiment.

and polarized with the electric vector parallel (‖) and perpendicular (⊥) to the plane of incidence. It will be observed that in the layer occupied by the alkali metal film the intensity of the ‖ case is very much greater than the ⊥ case, in agreement with the experimental finding that the photoelectric current is much greater when the electric vector is parallel to the plane of incidence. It will be further observed that at various distances above the surface the relative values for the ‖ and ⊥ conditions assume a series of widely variant values.

Considering now the right-hand side Fig. 1, we have indicated the alkali metal film as being separated from and tilted with respect to the platinum surface. It is obvious that if the film could be held suspended in space in the position indicated it would cut through the standing wave pattern at different points along its length and we should expect the variations of photoelectric current to be similar to the variations in the standing wave pattern indicated at the left. Thus for the height indicated by the lower dashed line the two currents due to ‖ and ⊥ light would be equal, while at the height indicated by the upper dashed line the ⊥ current would be much larger than the ‖, in striking contrast to the conditions usually found with photoelectrically active surfaces.

Practically, it is not possible to thus suspend the alkali metal film, so that it becomes necessary to interpose some supporting material. We have chosen for this a wedge of quartz which is put down by evaporating or subliming from a tungsten filament sheathed in quartz beads. By properly choosing the distance and location of the filament with respect to the platinum plate it is possible to obtain a layer of quartz relatively thick near the filament and thinner as the distance increases. Thus we obtain a wedgelike support for our film, which, though its variation in thickness is not entirely uniform, is still quite good enough for a qualitative study.

Of course the interposition of the refracting layer affects the energy pattern, but this being susceptible of computation, the essential features of the experiment are not impaired. The experiment then consists in the preparation of such a quartz wedge in an evacuated tube, and the introduction of a small quantity of an alkali metal such as caesium, which is allowed to vaporize spontaneously until a photoelectrically active conducting film is obtained. This is then investigated for photoelectric sensitiveness at various positions along the length of the wedge, for various angles of incidence and conditions of polarization, and at different wave-lengths. For comparison with these experimental measurements, computations are made of the electric energy density along a perfect wedge, using the optical constants of the materials involved. The agreement between the experimental and computed values constitutes the test of the assumptions made with regard to the rôle of the optical conditions in the photoelectric effect from thin films.

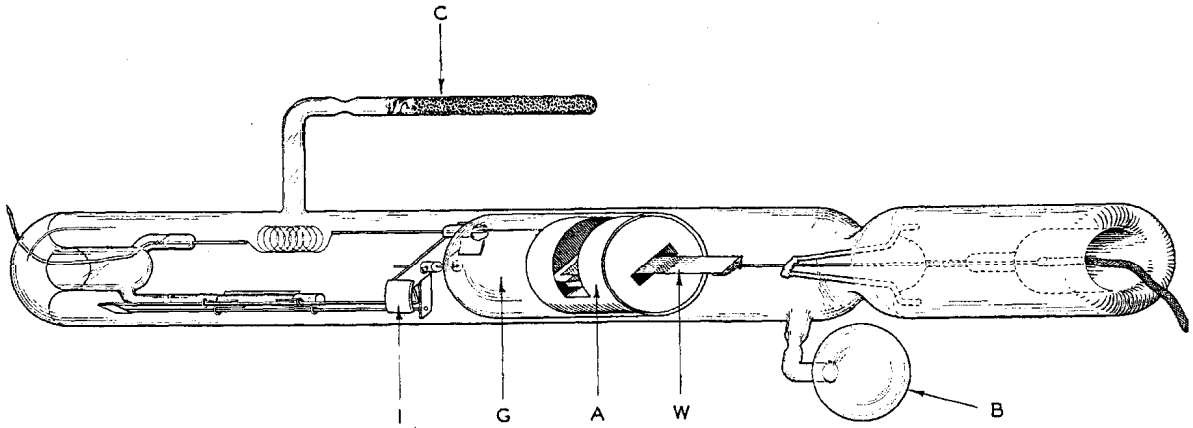

FIG. 2. Type of photoelectric cell used.

EXPERIMENTAL APPARATUS

A sketch of the type of photoelectric cell used in the experiments is given in Fig. 2. The quartz wedge on platinum (W) prepared in the manner described above, is mounted on a sliding carriage attached to the iron member I, so that it may be moved by means of an external magnet along the tube to expose it to the caesium vapor and also to place it conveniently within the collector. The tube is cylindrical in form and is mounted so that it may be moved parallel to its longitudinal axis and rotated so that the exciting light may strike the plate at any desired angle. The cradle for rotating it is provided with a divided circle so that angles may be chosen and read conveniently. The caesium is introduced by distillation into a side tube B from which a small quantity may be driven into the main tube, to serve as a supply for the spontaneous evaporation at room temperature, which is sufficient to deposit a photosensitive film. One of the chief experimental difficulties in this type of experiment is the diffusion of the caesium over all the walls of the tube, thereby introducing leakage currents. To minimize these, the cell was made very long and the anode was mounted in a glass sleeve G, closed at the end toward the leading-in wires. In addition, the amount of caesium introduced was purposely kept excessively small, the experiments being made with films which were very far from fully developed, but were nevertheless sufficiently sensitive for accurate measurement.

The appearance and properties of the quartz wedge deposited on the platinum plate warrant a brief description. Viewed by reflected light the wedge exhibits a series of faintly colored interference bands, some four or five millimeters apart. On long standing in the presence of alkali metal vapor these bands become intensified in color, because of the reflection of light back to the absorbing platinum surface. Ultimately the wedge becomes almost black, especially in the thicker portions. Part of the absorption of light is probably due to a slight granularity of the quartz deposit ("frilling"),[3] and this same roughness undoubtedly acts to depolarize the light and so impair the clear isolation of the photoelectric effects resulting from light polarized in the chosen planes. In the present experiments the measurements were all made with caesium films so thin as to have little effect on the intensity of the interference phenomena. For greater thicknesses the effect of the caesium film would have to be allowed for in the calculations which it was desired to check, thus introducing undesirable complications.

For illuminating the cell, a tungsten filament lamp with a quartz window was used in conjunction with a quartz monochromator and a quartz Rochon double image prism for polarizing the light. A variable angle prism made of two fused quartz wedges was introduced in the path of the double beam from the quartz Rochon prism, and shift from one plane of polarization to the other was made by rotation of the variable angle prism. The light spot used was about 1 mm in

[3] See Wood's Optics, 3rd Ed., p. 173.

diameter, and the optical adjustment was such that shifting of the spot on turning from one plane of polarization to the other was usually imperceptible. The photoelectric currents were read on a Compton electrometer with a high-resistance leak by the steady deflection method.

Calculation of the Electric Intensity in the Alkali Metal Film

The general methods by means of which the computations were made are entirely similar to those set forth in an earlier paper.[4] It was there shown that the electric force within a thin[5] film deposited on a massive base can be most easily found by first making some preliminary computations which have to do with reflection from the clean base. The exact process may be summed up in words as follows:

(a) We first ignore the presence of the film and find the phase and amplitude of the reflected beam just above the reflecting surface.

(b) We then add this vectorially to the electric force in the incident beam, thus getting the resultant force $\mathfrak{E}$ which would exist just above the surface if the film were not there.

(c) We then take account of the presence of the film by multiplying the normal component $\mathfrak{E}_z$ by a certain numerical factor g/g_1, which depends on the optical constants of the film, and which is the direct analogue for vibratory waves of the factor by which potential gradients change on crossing the boundary between materials of different dielectric constants.[6]

In this way we obtain the normal components of the electric force $\mathfrak{E}_1$ inside the film. The tangential components are the same as those of $\mathfrak{E}$.

Now the lamellar absorbing power of the film is known[7] to be proportional to $|\mathfrak{E}_1|^2$ which, in view of what we have said above, is $|\mathfrak{E}_x|^2+|\mathfrak{E}_y|^2+|g/g_1|^2|\mathfrak{E}_z|^2$. We can therefore find the amount of energy absorbed by the film directly from the components of electric intensity $|\mathfrak{E}_x|^2$, $|\mathfrak{E}_y|^2$, $|\mathfrak{E}_z|^2$ and the multiplying factor $|g/g_1|^2$.

Our present problem differs from the one previously discussed only in the nature of the base on which the film is deposited: where it was homogeneous before, it is now composed of massive platinum overlaid by a layer of quartz. As this difference does not affect the physical ideas outlined above, we can still compute our absorbing power from the same formula as before, provided we understand by $\mathfrak{E}_x$, $\mathfrak{E}_y$ and $\mathfrak{E}_z$ the components of electric force just above the stratified quartz-platinum surface. If, however, we assume the thickness of the quartz to be uniform throughout the region covered by our spot of light (although variable as the spot moves along the wedge), the amplitude and phase of the reflected light, and hence of $\mathfrak{E}$ also, can easily be found from the results of another paper.[8]

Thus we have at our disposal all the necessary machinery for carrying out the computational part of our program. Even so the matter of reducing the results to graphical form would still present rather serious practical difficulties except for the fortunate fact that the thickness of the quartz, t, and the wave-length of the light, λ, always appear in our reflection formulae in the combination t/λ, which may therefore be looked upon as a single variable. We can thus construct the master diagram of Fig. 3, which contains a family of curves corresponding to various angles of incidence, all of which have for abscissae the quantity t/λ.

In order to explain the ordinates on this master diagram it is necessary to go back and pick up a lost thread in our argument. We have said that the lamellar absorbing power of our film is proportional to $|\mathfrak{E}_x|^2+|\mathfrak{E}_y|^2+|g/g_1|^2|\mathfrak{E}_z|^2$, but we have so far said nothing about the factor of proportionality. From the exact relationship, which was given in Eq. (89) of *Plane Waves of Light III*, we find that this factor consists of $1/(\lambda \cos I)$, together with some incidental quantities which do not vary with λ, t or I, and are, therefore, of no interest in connection with our present study. Lumping these incidental factors

[4] Fry, *Plane Waves of Light III, Absorption by Metals*, J. O. S. A. 22, 307–332 (1932).

[5] The limits of thickness for which the approximation is valid are explained in reference 4, p. 322.

[6] In the case of a film of unit permeability with air or vacuum above it, g/g_1 reduces simply to $1/(N+iK_0)^2$, N and K_0 being the optical constants of the film.

[7] Reference 4, p. 324.

[8] Fry, *Plane Waves of Light II, Reflection and Refraction*, J. O. S. A. 16, 1–25 (1928). See in particular §17.

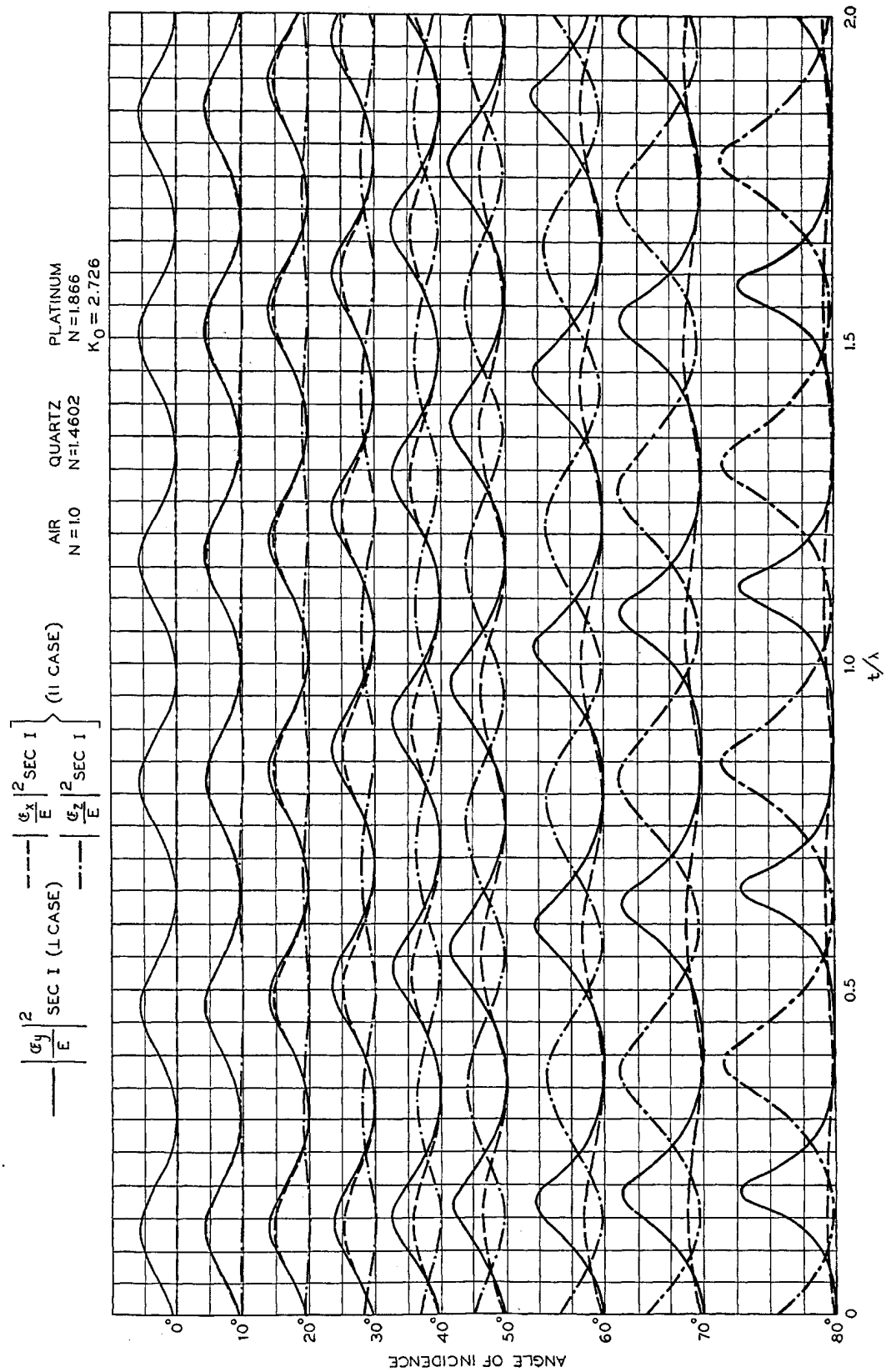

FIG. 3. Computed values of energy density at surface of quartz wedge on platinum, plotted against thickness/wave-length.

into the symbol B, we therefore have the equation

$$\lambda A_L = B(|\mathfrak{E}_x|^2 + |\mathfrak{E}_y|^2 + |g/g_1|^2|\mathfrak{E}_z|^2) \sec I.$$

We are now in position to explain the ordinates of our master diagram. They are exactly the quantities $|\mathfrak{E}_x|^2 \sec I$, $|\mathfrak{E}_y|^2 \sec I$, $|\mathfrak{E}_z|^2 \sec I$, which occur in this expression for λA_L.

The use of the diagram is simple. If our light is polarized with the electric vector normal to the plane of incidence, $\mathfrak{E}_x$ and $\mathfrak{E}_z$ are zero, and, except for a scale factor, the absorbing power of the film is obtained immediately by dividing the ordinate to the y-curve by the wave-length λ. If the light is polarized with its electric vector parallel to the plane of incidence we first read off the ordinate to the z-curve, multiply it by the "discontinuity factor" $|g/g_1|^2$, and then add the ordinate to the x-curve. When divided by λ the result is (except for the same scale factor B as before) the absorbing power for this plane of incidence.

For any given wave-length and angle of incidence the variation of absorbing power as our spot of light moves along the wedge can be obtained by reading from left to right along the curve which corresponds to the proper angle of incidence. It is not even necessary to divide by λ, which is constant along the curve, and can therefore be regarded as merged with the scale factor B.

Similarly, if the position of the spot of light on the wedge remains fixed and the angle of incidence is varied, we need only pick off points along a vertical line running through the whole family of curves. Again the divisor λ can be regarded as merged with the scale factor B.

If, on the other hand, we are interested in the variation of absorbing power with wave-length, all other factors remaining constant, we must choose the curve which corresponds to the proper angle of incidence and regard the abscissae as a scale of reciprocal wave-lengths. In this case the divisor λ becomes important.

Illustrations of the curves obtained in these various ways are given below in connection with the comparison between experimental and computed values.

Before leaving the master diagram Fig. 3, it is proper to point out that it is, in a strict sense, incomplete in that only a single pair of optical constants ($N=1.866$, $K_0=2.726$) have been used for platinum and that one value ($N=1.4602$) for the refractive index of quartz has been used throughout. Since both of these optical variables are reasonably constant through the visible region of the spectrum no serious error is introduced for our present purposes. Obviously for an absolutely complete treatment the variations of optical constants with wave-length should be introduced.

Experimental Results

The experimental results from which we give examples were obtained on two different tubes. The first of these, due to a loose contact in the platinum plate carriage could only be operated with the light incident at a considerable angle, so that with it measurements were made only at an angle of 60°. This tube served to give experimental data for the variation of photoelectric current along the wedge, and with wave-length, at the angle used. A second tube, which was free from this defect, was used for obtaining curves showing the variation of photoelectric effect with angle of illumination. Because of the use of different tubes, no direct correlations can be expected between the two sets of data; but this will be seen to be of little importance since all the significant behaviors predicted are found in one or the other of the two tubes.

Taking up first the variation of photoelectric current with thickness of the wedge, typical experimental results are shown in Fig. 4, where the abscissae give positions in millimeters of the spot of light relative to an origin near the thinnest point of the wedge, the latter point not being accurately determinable. In addition, because of the method of production of the wedge, it cannot be assumed that it is accurately triangular in vertical cross section. The abscissae therefore are to be considered merely as successive arbitrary points. Examination of the curves given in Fig. 4 shows at once a general agreement with the predictions of the theory as set forth in the master diagram. The emission curves pass through successive maxima and minima, the emissions for the two planes of polarization of the incident light reversing their position periodically. It is possible to pick out

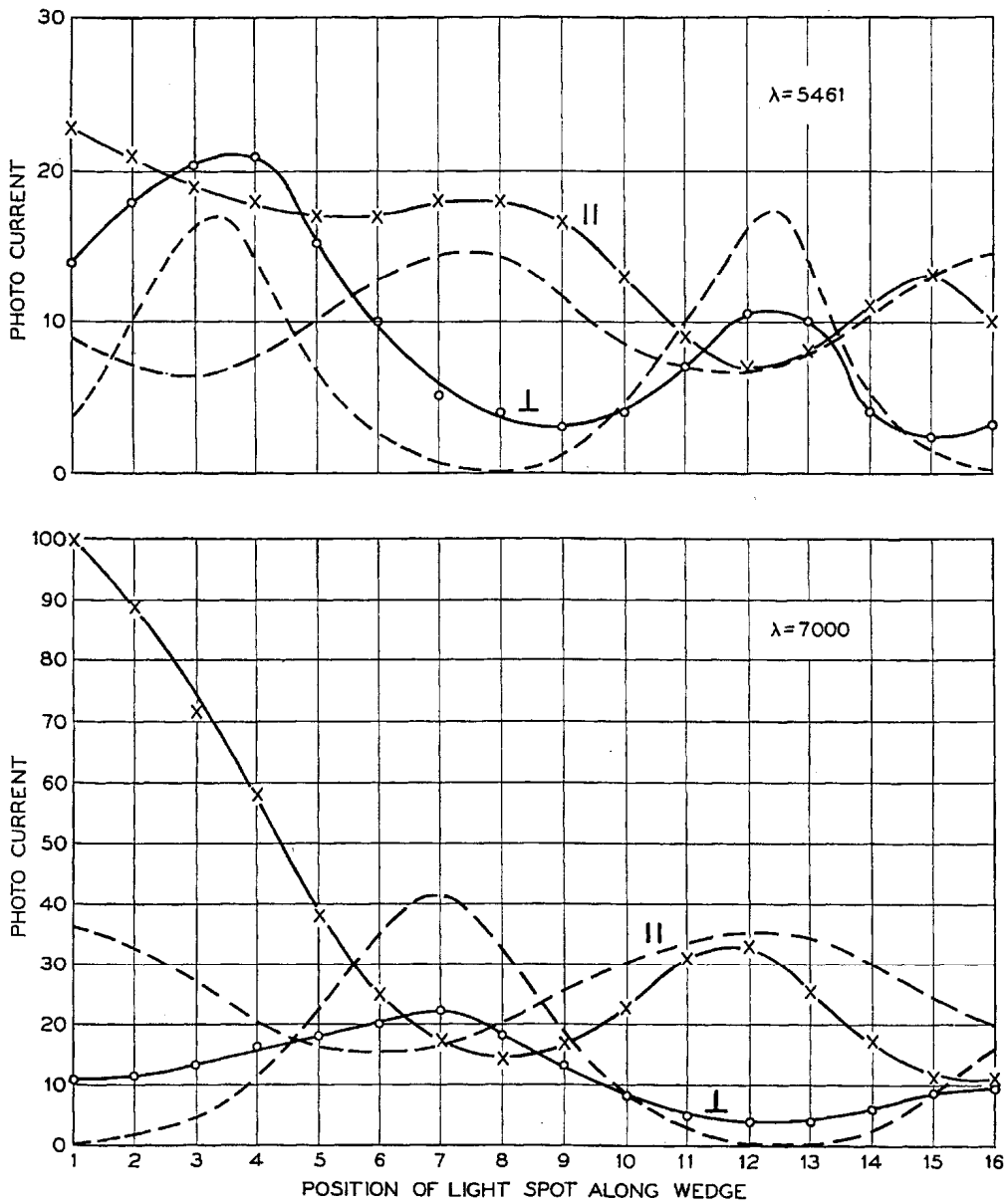

FIG. 4. Observed and computed values of photo-currents along wedge for 60° angle of incidence.

with some accuracy the actual thickness range covered by these measurements. By trial, it was found that the range from the positions 1 to 12, corresponds, in the case of wave-length 5461, to the extremes $t/\lambda=0.51$ and $t/\lambda=1.22$ on the 60° section of the master diagram, as is shown by the dashed curves in the figure, which were obtained by assuming $|g/g_1|^2=1$. For wave-length 7000, the corresponding range should be in the inverse ratio of wave-lengths, that is, $t/\lambda=0.4$ and 0.95. By using these values in the master diagram the dashed curves in the lower figure are obtained, and it is seen that the maxima and minima have shifted quite closely in the manner to be expected.

It should be pointed out that for several reasons a positional and qualitative agreement is all that can be expected. For one thing, the spot of light used is relatively large with respect to the interference bands which are visible on examining the wedge. For another thing, the quartz wedge undoubtedly scatters considerable

light, thus deviating from the condition of transparency and specular surface which theory demands, whereby among other things the photo-currents suffer progressive diminution in value as the wedge increases in thickness. The fact that the wedge is probably not accurately flat on its top surface has already been mentioned. These more or less inevitable deviations from ideal conditions result in considerable flattening out of the maxima and minima and some shifting of their positions. The agreement between theory and experiment is, considering these limitations, very satisfactory.

Turning now to the distribution of photoelectric current with wave-length at different positions along the wedge, we show first in Fig. 5 (upper left-hand panel) the photoelectric emission with wave-length for clean platinum, from a section of the cathode which was shielded from the quartz carrying filament. This shows the rise of emission towards shorter wave-lengths and the somewhat greater emission for $\parallel$ light which is characteristic of the very thin film of caesium on platinum. No maxima or minima of emission occur in the wave-length region studied. In succeeding panels of the figure are shown wave-length distribution curves for positions 4, 7, 10 and 13 along the wedge. These are of quite different and extremely varied character, exhibiting not only pronounced maxima and minima of emission through the visible spectrum but periodic reversals of the strength of the photoelectric current for the two planes of polarization. Maxima in fact are present showing much the character of those produced by the action of a sensitizing glow discharge or other well-known procedures.

It is possible, by proper use of the master diagram, to check the experimental results with the theoretical ones. In order to make a complete check we would have to know the intrinsic photoelectric emissivity of the alkali metal, as a function of wave-length, and the multiplying factor by which the z component must be modified to take account of the optical constants of the film. These factors are not at present definitely known for caesium; the multiplying factor of the z component in fact probably depends upon the state of aggregation of the film, and we cannot even be sure that it is the same when it is deposited upon clean platinum and on the quartz base. In default of this information we have made the short cut of simply multiplying the experimental emission curves for the caesium film on clean platinum (upper left-hand panel of the figure) by the ratios of emission indicated by the master diagram, for various values of t/λ, arbitrarily selecting scale factors for the $\parallel$ and $\perp$ curves. The results are well illustrated by the lower right-hand panel, where curves so computed for $t/\lambda = 0.5$ are shown. These agree quite closely with the experimental curves for position 10 of this series[9] (upper right-hand panel) on the wedge, and show that the major characteristics of the experimental results are in satisfactory agreement with the theory.

The third set of data to be considered are the angle curves. The typical form of these curves for a thin alkali metal film on a base such as platinum is shown by the upper left-hand panel of Fig. 6. The emission due to light polarized with the electric vector in the plane of incidence rises to a sharp maximum at about 80° and falls rapidly to 90°, while for light polarized in the other plane, the emission falls off steadily from 0° to 90°. In the succeeding panels of Fig. 6 are shown a family of angle curves obtained for a series of positions along the wedge in the second tube. These exhibit a most extraordinary range of characteristics.[10] The emissions for the two planes of polarization alternate in position, and in place of the single maximum of emission characteristic of the platinum base we have multiple maxima exhibited. Again, as in the previous case, it is possible to build up from our master diagram angle curves which exhibit the dominant characteristics found experimentally. Illustrations of these are given in Fig. 7, computed by assuming, for convenience, the value unity for the multiplying factor $|g/g_1|^2$. These computed curves show in general the same type of behavior as the experimental ones. Because of the roughness of

[9] The curve shapes repeat the same general characteristics for a series of thicknesses, so that a greater value of t/λ would agree with the experimental data about as well, corresponding to the thickness estimate made from Fig. 4.

[10] The non-coincidence of the curves for 0° in certain cases is probably due to a slight shift of the light spot in turning from one plane of polarization to the other, in conjunction with irregularities in the wedge structure.

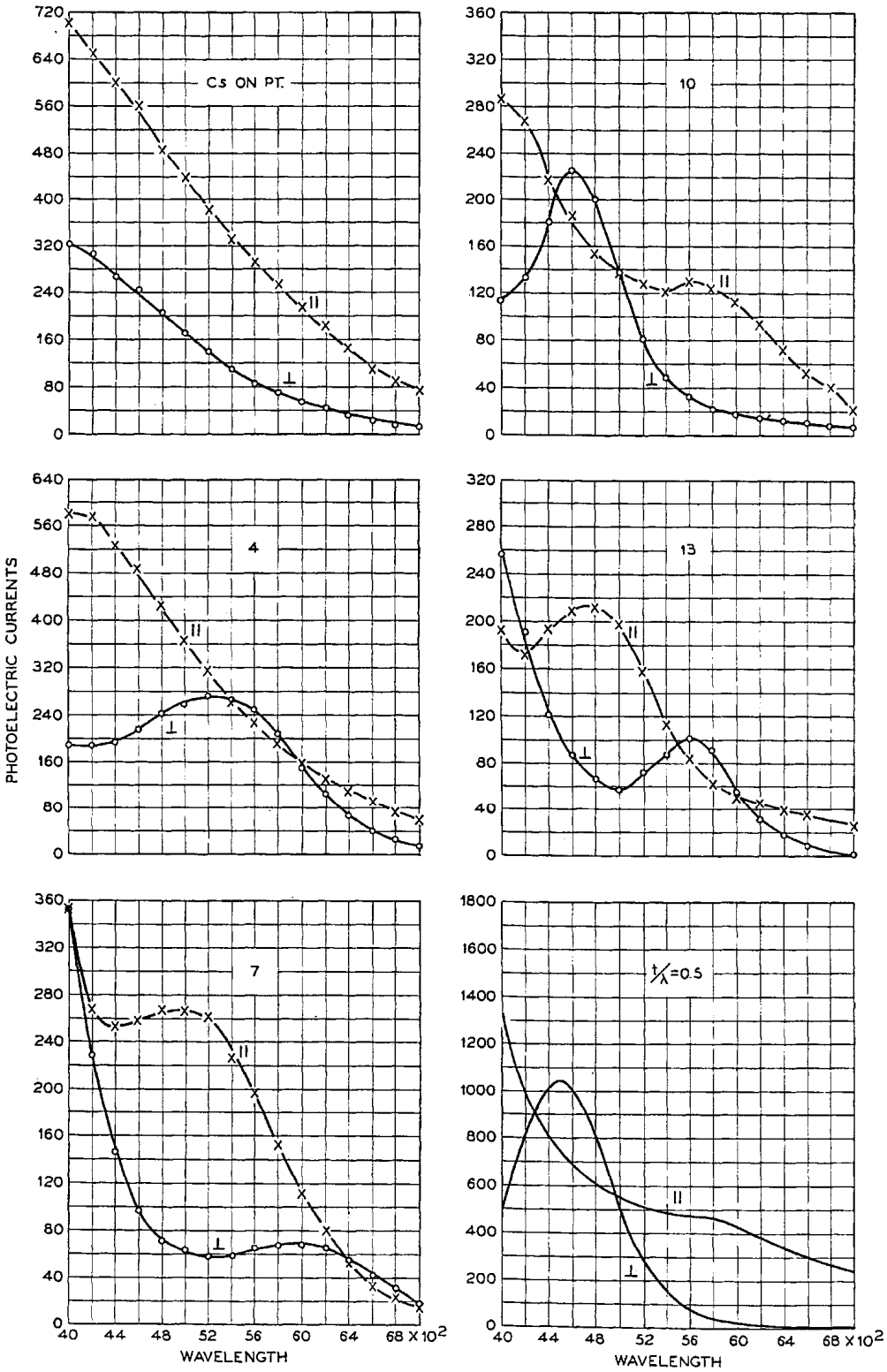

FIG. 5. Wave-length distribution of photo-currents for various positions on wedge.

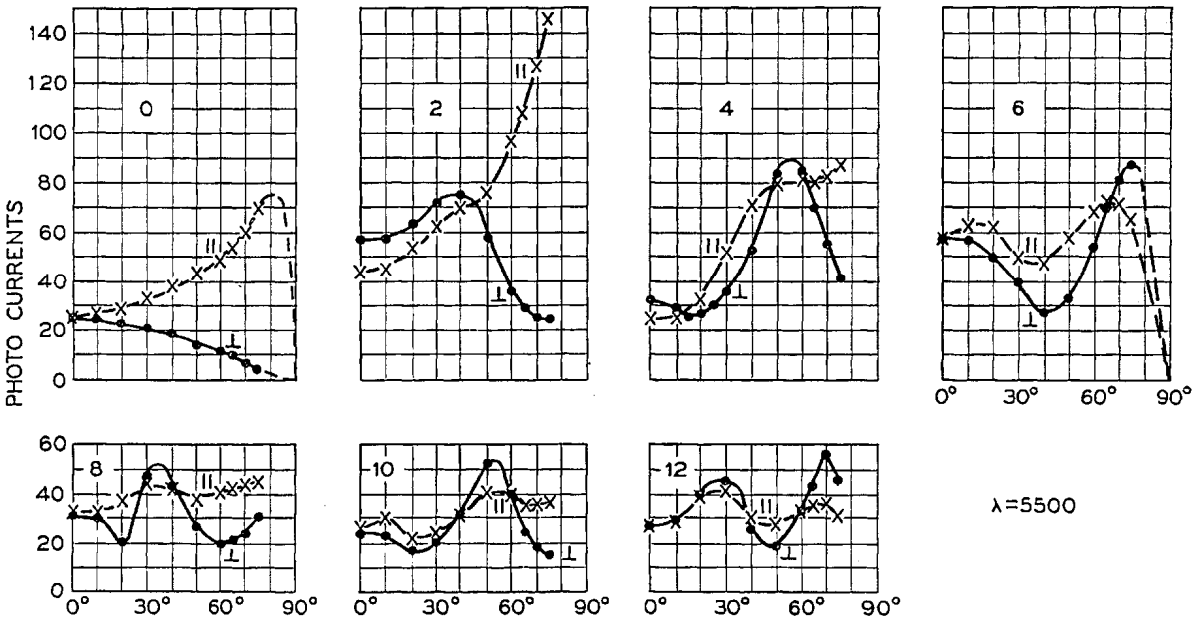

FIG. 6. Angle curves at various positions along wedge.

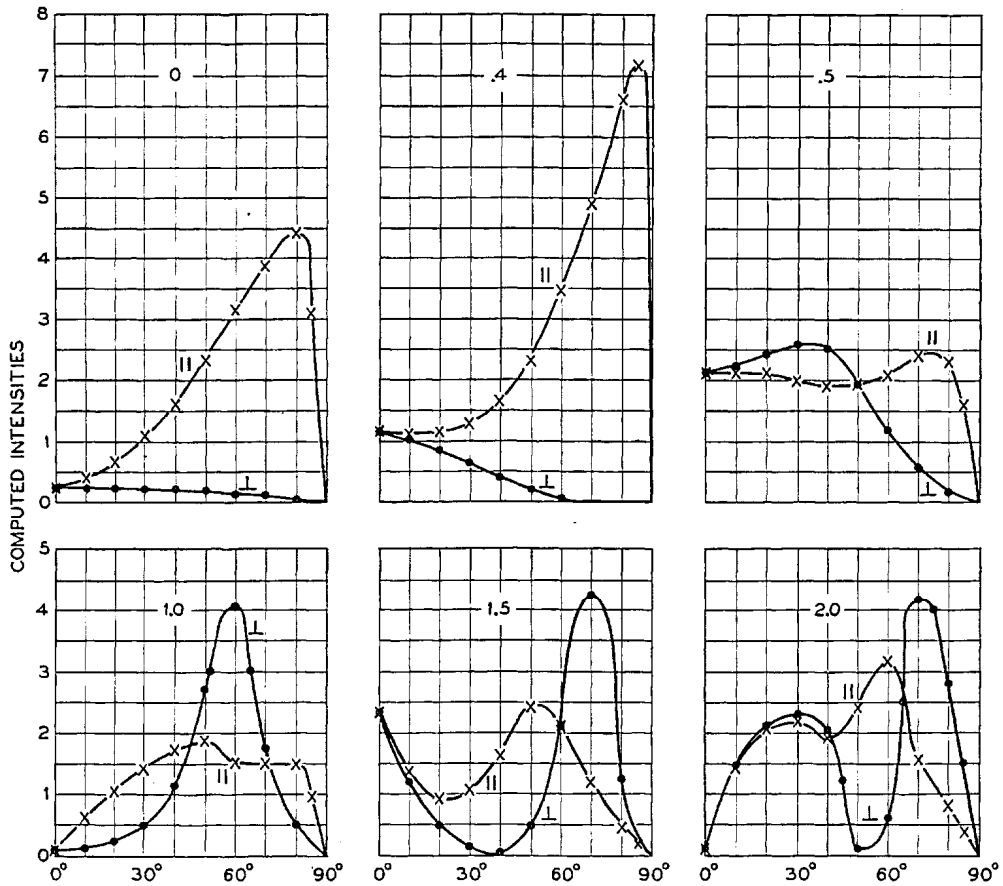

FIG. 7. Computed angle curves for various values of t/λ.

the quartz, already mentioned, the photocurrents are relatively too large at the small angles, but with this allowed for the check is quite satisfactory. It appears from this test, that the quartz wedge in this second tube, over the region which it was possible to measure, is everywhere of considerable thickness, the angle curves characteristic of thicknesses less than $t/\lambda = 0.4$ not being found. We have, however, found these in other experiments which will be reported on in another connection.

Discussion

The results of this study, considered from an optical standpoint, constitute a further and more detailed confirmation of the point in classical wave theory investigated by Wiener. By the use of the photoelectric probe surface quantitative measurements have been possible in place of the purely qualitative observations which the photographic and fluorescent methods yield. While the measurements here recorded are in certain respects rather crude, it appears likely that if the scale of the apparatus were enlarged, if methods of preparing considerably longer wedges of clear transparent material were developed, and if the intrinsic photo-emissivity and optical constants of the alkali metal film were accurately known and used, a very complete quantitative check on the theoretical computations would be obtained. There is probably no doubt at the present time that the classical wave theory covers the case, and pushing the experiments beyond the present point is hardly warranted.

From the standpoint of photoelectric theory, for which the study was undertaken, the results give added support to the line on which we are studying the photoelectric effect from thin films of alkali metal. The experiment has in fact carried the investigation of the relation between electric intensity and photoelectric current up away from the metallic base, to which experiments were previously confined, into the space above. Here, according to the theory, quite unusual photoelectric phenomena were to be expected, and have now been observed.

The experiment also has an important bearing on the whole question of spectral maxima and minima of emission in photoelectric cells in which the alkali metal surface has been given any sort of sensitizing treatment. The similarity of the maxima of emission here brought about by lifting the sensitive layer away from the underlying metal, to the maxima produced by subjecting the surface to a hydrogen glow discharge and other processes is so striking as to suggest the futility of theoretical speculation correlating these maxima with atomic, crystalline, or wave mechanical factors until the purely optical factors have been evaluated.[11] A case in point is the very efficient type of cell in which a sensitive surface containing caesium is developed on an oxidized silver plate. It has recently been found possible in these laboratories to produce cells of this type with plates of specular silver. These cells exhibit interference colors, which indicate that the silver oxide acts as a transparent supporting layer, similar to the quartz wedge here used. The spectral maxima and minima of emission exhibited by these cells are undoubtedly influenced by the optical conditions described in this paper, and these latter must be allowed for before intrinsic emissive properties can really be established, much less explained. The subject matter of this paper may be considered to some extent as preparatory work to the further study of the caesium-silver-oxide cell.

We are greatly indebted to Mr. G. R. Stilwell for the measurements reported in this paper, and to Miss C. L. Froelich for the extensive computations necessary.

[11] The interesting experiments of Suhrmann (Phys. Zeits. 32, 216 (1931)) where exposure to vapors of naphthalene and paraffin modified the selective photoelectric effect of a potassium surface, are possibly subject to reinterpretation on an optical rather than the chemical basis favored by Suhrmann.