THE DISTRIBUTION IN DIRECTION OF PHOTOELECTRONS FROM ALKALI METAL SURFACES

By Herbert E. Ives, A. R. Olpin and A. L. Johnsrud

Abstract

An experimental study of the distribution in direction of photoelectrons emitted from alkali metal surfaces irradiated by light incident at varions angles and polarized in different planes.—The alkali metal surfaces used were of two sorts: (1) liquid alloys of sodium and potassium, (2) thin films of potassium or rubidium on polished platinum. In all cases the alkali metal surface was at the center of a large spherical enclosing anode, provided either with collecting tabs at various angular positions or with an exploring finger. It is found that the emission closely obeys Lambert's law, but that the ellipse by which the emission is represented, in polar coordinates, is more elongated normally to the surface for perpendicularly incident light than for obliquely, when the direction of the electric vector is in both cases parallel to the surface, and still more elongated for obliquely incident light with the electric vector in the plane of incidence. The distribution curves are all perfectly symmetrical about the normal to the surface, showing no tendency to follow the direction of the electric vector.

Introduction

THIS investigation was undertaken for the purpose of acquiring additional information on the striking differences in photoelectric emission from certain alkali metal surfaces when the plane of polarization of obliquely incident light is changed. The well-known variations in emission as the electric vector is altered from vibrating parallel to the plane of incidence to vibrating perpendicular to it are two in number; first, a change in the amount of the emission, much greater in the characteristic cases than can be accounted for by the gross optical absorption of the surface; and second, the development of a pronounced maximum in the spectral distribution of emission. In addition to these well established effects, work by Hughes[1] some ten years ago indicated a difference in the direction of emission of photoelectrons as the plane of polarization of the exciting light was changed. It was for the purpose of obtaining more exact information on this point than Hughes' work afforded that this investigation was made. Our data, as will be seen, confirm Hughes' conclusions, but are more detailed and complete in a quantitative way than his.

Direction distribution measurements of photoelectrons from other than alkali metal surfaces have been made by Gardner,[2] who used a platinum surface and measured the photoelectrons received by an exploring finger in various angular positions with respect to the emitting surface. He found the emission to be greatest normal to the surface, falllng off rapidly therefrom. His work will be discussed further in the consideration of our own.

[1] Hughes, Phys. Rev. **10**, 5 (1917).
[2] Gardner, Phys. Rev. **8**, 70 (1916).

The distribution-in-direction of photo-electrons produced by x-rays has been the subject of considerable study recently; particularly by the cloud expansion method.[3] The results of these experiments are generally in agreement with the idea that the photoelectrons tend to follow the direction of the electric vector. Since there have been various suggestions that the peculiar behavior of the photoelectric emission from alkali metal surfaces may be due to a similar tendency for the electrons to follow the electric vector, it is a matter of some interest to determine if such is the case. The work of Hughes, above quoted, was not done with apparatus which would make possible an unambiguous answer to this question.

Terminology

Pohl and Pringsheim[4] in their extensive and important work on the photoelectric effect assumed that the great enhancement of the photoelectric emission when the electric vector is parallel to the plane of incidence is always associated with the presence of a maximum of emission in the spectrum, characteristic of the material (although the converse of this was not always true.) They also assumed that these two effects were both characteristic of the pure alkali metals, for instance sodium and potassium, although their actual work, in which the two effects were present together, was done on sodium-potassium alloys. The photoelectric emission due to light polarized with the electric vector perpendicular to the plane of incidence was called by Pohl and Pringsheim the "normal" photoelectric effect, that due to light polarized with the electric vector parallel to the plane of incidence they called the "selective" photoelectric effect. These terms have come into very general use.

Recent work has shown that the assumptions as to the invariable association of enhanced emission with a spectral maximum characteristic of the material, and of these properties being characteristic of the pure alkali metals, cannot be supported.[5] The pure alkali metals, while showing a spectral maximum, do not exhibit the large ratio of emissions. Their alloys exhibit varying ratios of emission depending on their exact composition.[6] Again while the pure alkali metals, in the liquid state, do not exhibit the large ratio of emissions, they exhibit this phenomenon to a remarkable degree, when present in the form of thin films upon other metals such as platinum. A thin film of alkali metal does not however exhibit a spectral maximum, at the wave-length formerly supposed to be characteristic of it.[7]

It is evident from these facts that the terms "normal" and "selective" are inadequate to describe all the observed phenomenon with proper discrimination and that to group together, under these terms, all the

[3] See Watson, Proc. Nat. Acad. Sci. **13,** No. 8 (1927) for references.
[4] See Pohl and Pringsheim, "Die Lichtelektrische Erscheinungen," Viehweg, 1914.
[5] Ives and Johnsrud, Astrophys. J. **60,** 4 (Nov. 1924).
[6] Ives and Stillwell, Phys. Rev. **29,** 252 (Feb. 1927).
[7] Ives, Astrophys. J. **60,** 4 (Nov. 1924).

phenomena of emission which occur as the plane of polarization is changed would be dangerous.

In addition to the reasons given for not using the terms "normal" and "selective," we have an additional fact which has come out of the present work. It has been commonly assumed that the "normal" effect is obtained either with obliquely incident light in which the electric vector is parallel to the surface, or with perpendicularly incident light, since the electric vector is in this case also parallel to the surface. We have, however, in this work, found differences in the distribution curves for those two cases, that is, differences which depend solely upon the angle of incidence. We have then, if possible, to find terms to describe the three following cases: First, normally incident light, in which the electric vector is of necessity parallel to the surface. Second, obliquely incident light in which the electric vector is perpendicular to the plane of incidence. Third, obliquely incident light in which the electric vector is parallel to the plane of incidence. The choice of appropriate terms has proved a matter of great difficulty. The choice is complicated by the fact that the definition of "plane of polarization" which is used in physical optics was unfortunately chosen so that it conveys just the opposite idea to that which we wish when considering the direction of vibration. It would make the present paper excessively long, and would make the descriptions of experimental additions exceedingly clumsy, if phrases or adjectives completely descriptive of the conditions of incident llght were used in every case. It has therefore been decided to make this description by means of symbols. In order to make our descriptions conform as closely as possible to previous work, we have used the symbols introduced by Pohl and Pringsheim for obliquely incident light polarized in the two characteristic planes, and have added to these a third symbol for normally incident light. In accordance with this decision the symbols with their meanings are as follows: $\stackrel{\perp}{=}$–normally incident light (electric vector parallel to the surface); $\parallel$–obliquely incident light, with the electric vector parallel to the plane of incidence; $\perp$–obliquely incident light with the electric vector perpendicular to the plane of incidence.

Apparatus

The photoelectric cells used for this study were of special design approximating more or less closely to the simple geometrical form considered in the theoretical study reported in the preceding paper.[8] In all cases the cathode was at the center of a spherical enclosure which formed the anode. Several forms of cathode were used in various cells. In the earliest work, a flat polished platinum plate was used on which a sensitive alkali metal surface was formed by sublimation, as described in earlier papers. In later cells the cathode was a hollow spherical platinum ball of dimensions such that the complete cell approximated very closely to the form postulated in the theoretical study. The photoelectric surface was formed in these cells by

[8] Fry and Ives, Phys. Rev. **31**, 000 (1928).

sublimation. In other cells the cathode was of liquid sodium-potassium alloy in a cup. To insure against charging of the walls of this cup the glass

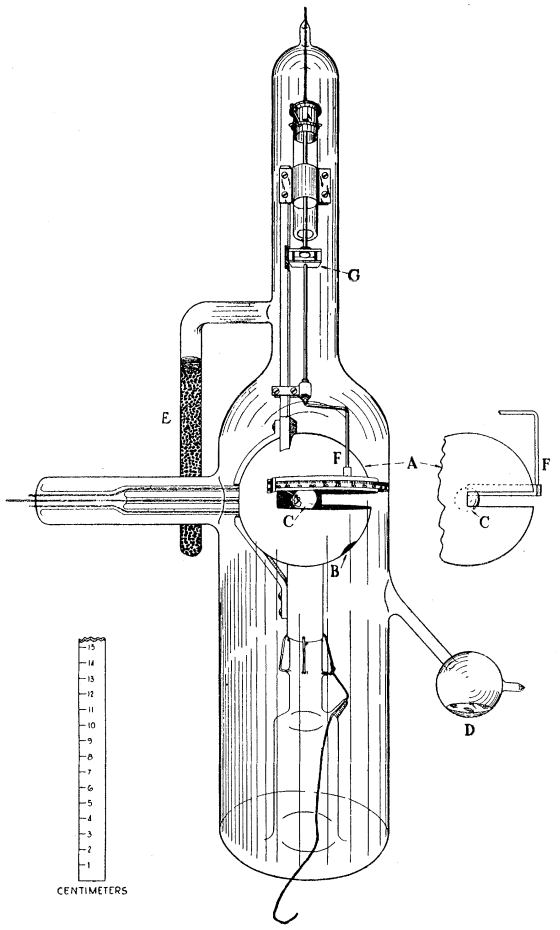

Fig. 1. Moving vane type of photoelectric cell. The anode *A* consists of a spherical copper shell, coated inside and out with turpentine soot. Concentric within is the hollow spherical platinum ball *C* used as cathode. Rb was sublimed from side tube *D* through opening *B* of anode onto the cathode. The thickness of cathode layer could be controlled by heating the filament within the Pt ball. Light focussed on the cathode was incident and reflected through a narrow slit in side of anode. Electrons reaching anode at any angle with respect to normal to cathode could be measured by setting the moving finger *F* at that angle, the angular setting being made by rotating iron coupling *G* with electromagnets. In order to insure that the position of the finger in no way influenced the field between cathode and anode, a curved strip of soot-coated copper was fastened to the anode directly behind the path of the movable finger as shown in inset. Charcoal tube *E* was immersed in liquid air to insure a good vacuum.

was nickel coated and the alloy flowed in until flush with the top. Details of two representative designs are shown in Figs. 1 and 2. During the course

of the study, measurements were made on eleven different photoelectric cells conforming more or less closely to the types shown.

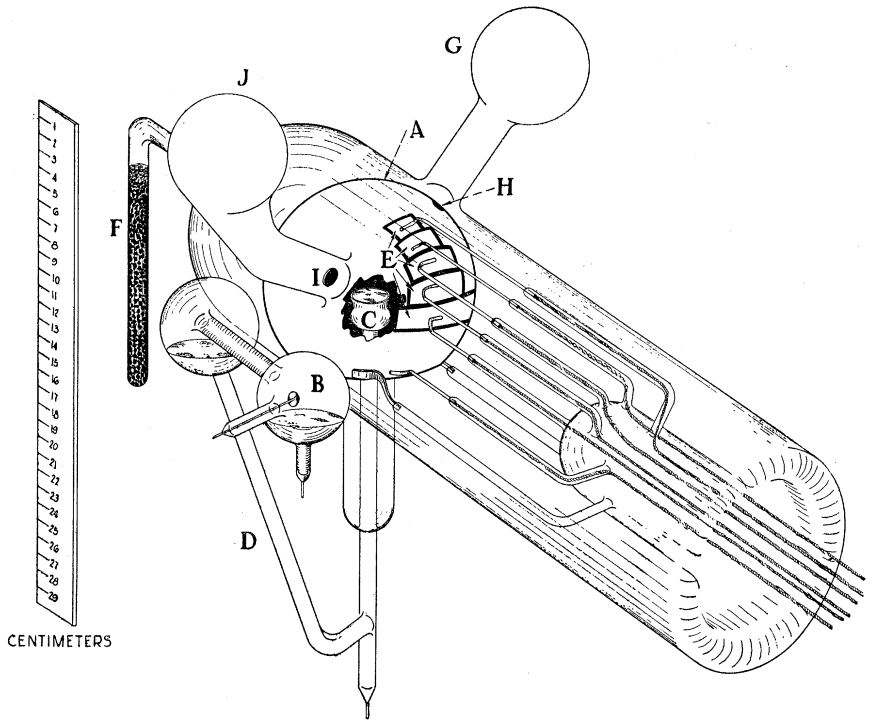

Fig. 2. Isolated tab type photoelectric cell. Soot-coated copper shell *A* serves as anode and nickel-plated glass cup *C* filled with NaK alloy forms the cathode. After evacuating cell the alloy was poured from side tube *B* (which has electrodes for measuring the ratio of photoelectric emissions for light ∥ and light ⊥) through connecting tube *D* and allowed to rise in cup *C* until the level was exactly that of top of cup. Light was incident by way of side tube *G* through small hole *H* onto alloy surface and reflected through opening *I* into side tube *J* where reflected around and around until absorbed entirely. Tubes *G* and *J* were blackened completely with exception of nose of *G* wherein the light entered. Isolated tabs *E* having separate lead-in wires collected the electrons at various angles with respect to normal to cathode. Charcoal tube *F* placed in liquid air maintains good vacuum.

For purposes of reference the following list shows the structural type of each of the cells for which experimental data are given in the figures illustrating the paper.

Cell No.		
	70 K	Moving vane, flat platinum plate cathode.
	119 Rb	Moving vane, spherical platinum cathode.
	121 Rb	Flat platinum plate cathode, entirely enclosing anode without tabs or vane.
	165 Na K	Multiple tab, liquid alloy in cup.
	171 Na K	" " " " " "
	183 Na K	" " " " " "
	187 K	Multiple tab, solidified potassium in cup.

In order to make the necessary measurements for different angular positions from the cathode, two different devices were used. In certain of the cells a moving finger was provided arranged to rotate between a double wall in the anode, thus providing for an unchanging electrical field while at the same time the current to be measured was only that received by the small area. This form of cell is shown in Fig. 1. In other cells a number of isolated tabs were placed at appropriate positions in the spherical anode and were connected to separate leading-in wires. Such a cell is shown in Fig. 2 and the general method of electrical connection is shown in Fig. 3.

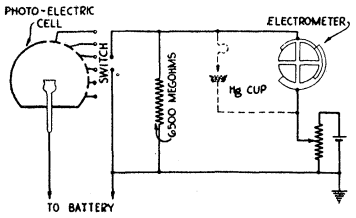

Fig. 3. General method of electrical connection. (See Fig. 4 also.)

In all the work here described except where otherwise noted, the exciting light was blue light of wave-length 4358 of the mercury spectrum as obtained from a quartz mercury arc and filtered through a special filter of blue glass combined with several layers of aesculin in gelatin. This filter while transmitting the blue light, eliminated the violet line at 4038 so completely that extreme over-exposure in a quartz spectrograph failed to show any trace of it.

In the greater part of the work the obliquely incident light was incident at an angle of 60° and was passed through a multiple Ahrens prism for polarization purposes. The prism was arranged so that its azimuth could be changed by cords operated by the observer.

All measurements were made with a Compton electrometer, the steady deflection method being used, that is, the electrometer measured the potential drop across a high resistance in series with the cell. As a high resistance, a xylol-alcohol sealed cell with a resistance of 6,500 megohms was used. Thus with 90 volts on the needle a sensitivity of approximately 300 cm/volt was obtained. The electrometer was enclosed in an air-tight box with drying material and the photoelectric cells were similarly entirely enclosed. Fig. 4 shows a photograph of the photoelectric cell box open with a cell in place. In the foreground will be seen a series of six cords operating mercury switches. These were used with those of the cells in which the receiving tabs were fixed in position and provided means for switching from one electrode to another. In this respect the tab cells were better than the finger cells, for with these it was necessary to open the door of the iron box encasing the photoelectric cell every time adjustment for a new angle was made. Thus the finger cells were usable only on dry days. As a matter of fact, the finger cells were used only when the other type was inadequate.

Details of Measurements

A series of measurements for showing the distribution of photoelectrons in direction for any condition of the exciting light consists of successive measurements either with a measuring finger in a series of positions or from

several of the isolated tabs in the spherical anode. The comparatively simple procedure just outlined is, however, greatly complicated by experimental difficulties. One of the most serious difficulties of all in the present study has

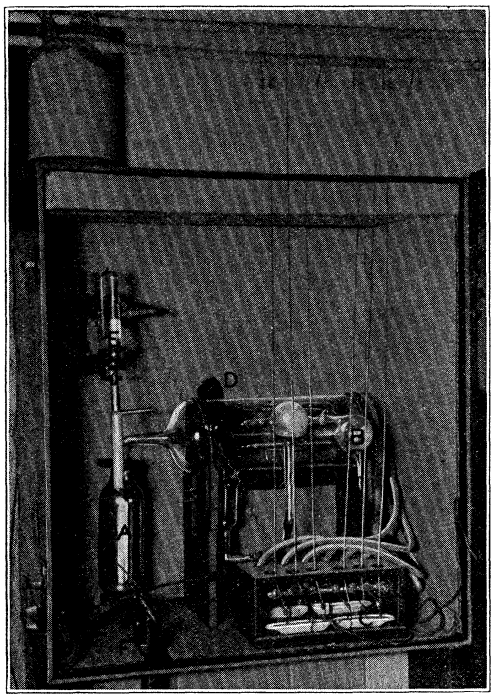

Fig. 4. Photograph of a photoelectric cell in place. *A*, liquid air flask on charcoal tube; *B*, small photoelectric cell connected with large one to permit study of relative emissions for light ∥ and ⊥ before pouring alloy into cathode stem of large cell (Fig. 2); *C*, switching device whereby each tab of cell (Fig. 2) can be disconnected from ground and connected to the electrometer in turn by pulling proper silken thread leading out through top of shielding box; *D*, lens and prism unit through which light was admitted; *E*, xylol-alcohol resistance across electrometer; *F*, carefully insulated and shielded wire leading to electrometer.

been the characteristic one in working with alkali metals in high vacua that all parts of the apparatus become photo-sensitive. The nature of the errors due to this cause are strikingly illustrated by Figs. 5 and 6. In these figures the crosses represent the distribution curve as obtained by a finger moving in the plane of incidence, with obliquely incident light. The distribution is represented by an ellipse. The small circles show the results obtained with light incident normally on the surface. In this case the distribution curve consists of two wings separated by a pronounced depression in the middle.

This apparent difference between the distribution curves for the two illuminations is entirely spurious, and is due to the fact that the flat platinum plate which was the cathode reflects light directly back to the exploring finger when it stands opposite the plate. The result is a photoelectric current back

from the finger which may be so great as actually to carry the minimum to negative values, as shown in Fig. 6. This sensitiveness of the collector is also exhibited when voltage-current curves are made to the entire collector by a current in the reverse direction when the central electrode is made positive.

In order to prevent the anode from becoming sensitive, we have made use of an earlier observation that carbon, in particular soot, does not absorb alkali metal vapor to the point of becoming sensitive to light nearly so quickly as most of the metals do. The spherical anodes were accordingly in all cases given a coating of soot. Even so, in the course of time some sensitiveness develops, particularly for long wave radiation, so that it was necessary to make frequent voltage-current curves to make sure that no sensitiveness had developed. Because of the fact that the sensitiveness developed by the soot coating was relatively greater for long wave energy than the sensitive-

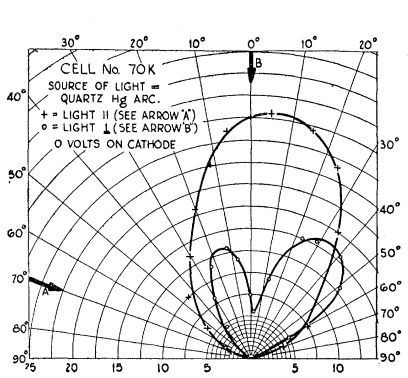

FIG. 5

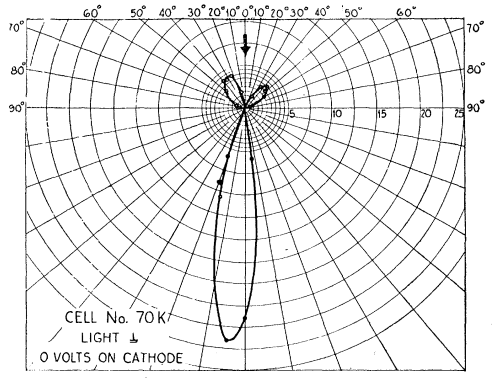

FIG. 6

Fig. 5. Distorted angular distribution curve. Counter-emission of electrons from a photo-sensitive anode greatly decreased the measured current for settings of finger such that light was reflected on it. Arrows show direction of incidence of light.

Fig. 6. Showing still greater distortion of angular distribution curve. For settings of finger at small angles to normal and light normally incident, anode to cathode current was much larger than that from cathode to anode.

ness of the cathode, it was not possible to make satisfactory distribution curves with green or yellow light.

The danger of back currents from the anode when photo-sensitive makes careful and accurate optical alignment extremely important. Accuracy in these adjustments is essential for other reasons. If, for instance, the lens and prism set-up should be such that the path of the incident light were at any place deviated from a straight line the effect of rotating the prism would be to shift the position of the incident beam on the cathode. The result would be that the angle between the normal at the illuminated spot and a fixed collector might vary slightly for light $\perp$ and light $\parallel$, the apparent photo-electric sensitivity of the spot illuminated might vary with the polarization of the light, and, of greater importance still, the reflected light might fall more directly on the anode in one case than in another. This latter problem

was a serious one in that the incident light beam had to be introduced onto the cathode through a small opening in the spherical metal anode and the reflected beam allowed to pass out of the tube through a similar opening.

To facilitate the problem of getting the light onto the cathode and out of the cell again without illuminating the anode in any way the beam was made as small as possible. This small beam was obtained by passing the light from the arc through a specially constructed collimator having within it soot coated apertures of about 6 mm diameter at intervals of 2 to 4 cm. This cut out all the effects that might result from stray or reflected light. The direct beam then passed through a carefully machine-centered lens and prism system; one lens changing the light to parallel rays while it passed through the multi-Ahrens prism and the other focussing the polarized light on the cathode of the photoelectric cell. An additional diaphragm or aperture reduced the width of the pencil still more before it entered the cell.

Fig. 2 shows an added precaution taken in the case of some of the more important cells. On the side of the incident light and projecting toward the source was an arm of the tube blackened on its sides. Any diffused light that may have originated as the incident beam passed through the glass wall at the end of this arm was absorbed by the black walls of this tube. Then, after the light was reflected from the cathode through the small opening in the anode, it entered another arm blackened on the outside and shaped to form a light trap.

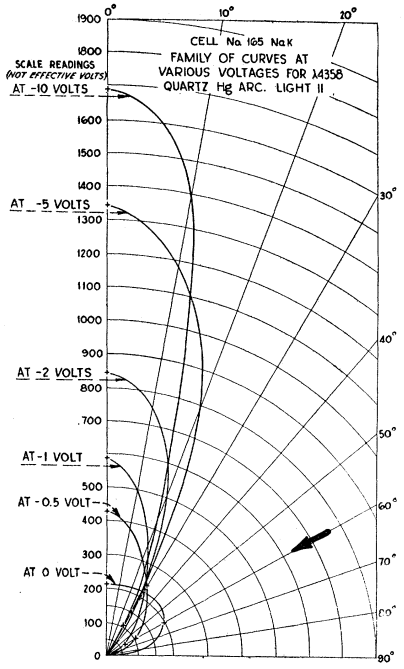

Fig. 7. Angular distribution of electron emission for various accelerating potentials. Arrow shows angle of incidence of light.

While this cutting down to a minimum of the size of the incident light pencil inevitably reduced to some extent the accuracy of the results, this condition was necessary to permit reliable comparison of the observed deflections for light polarized in different planes and for different angles. By keeping the electrometer deflections small the *IR* drop across the high resistance was made negligible and the tab or finger was kept at the same potential as the remainder of the anode. Moreover, the more nearly the illuminated spot assumed infinitesimal proportions the more nearly the observations should approach the theoretical requirements, particularly where the cathode consisted of a small sphere.

In order that the size of the currents might not fall to inconveniently low values for the tabs at large angles to normal from the cathode, these tabs

were in several cells increased in dimensions for the larger angles as shown in Fig. 2. The results then obtained were reduced to the current per unit area basis for study. This gradual increase in the size of the tabs with α would not have been permissible had not the moving vane type photoelectric cell first revealed the symmetry of the angular distribution curve about the normal to the surface.

Early in the work we had to consider the question of the proper value for the applied electric field. It was found that the distribution curves varied from a flat to a long ellipse as the potential difference between cathode and anode was increased. This phenomenon is of course entirely to be expected since the stronger the accelerating field the greater the proportion of the electrons ejected at large angles of incidence which will be deviated toward the normal. This effect is discussed in the theoretical paper already referred to and is illustrated by the experimental data of Fig. 7. The curves connecting the limited number of experimentally determined points were drawn according to the theory worked out by Fry and Ives.

The first assumption would probably be that the field to use would be the effective zero, which is to be determined by taking a voltage-current curve to the complete anode and finding the point at which saturation occurs. Actually, as has been pointed out in the theoretical study, the true initial distribution-in-direction occurs at zero field only if the emitting element is at the exact center of the spherical anode. Where, as is the case with the concentric spherical electrodes, chosen, for reasons of simplicity, in calculating the effects of various applied fields, the emitting element is off center, the true initial distribution is represented most nearly at some small retarding potential. The experimental results are hence subject to interpretation by reference to the design of the tube used.

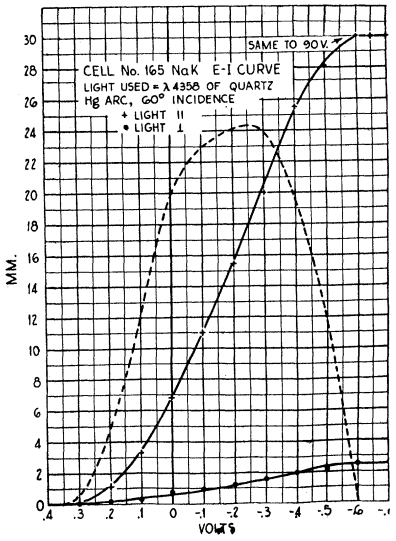

Fig. 8 (a). Voltage-current curves taken soon after cell was made. Broken line shows relative energy distribution of emitted electrons as given by derivative of *E-I* curve.

Experimental Results

As a starting point for a study of the direction distribution curves, it is necessary to determine the voltage-current curve for the total current received by the enclosing anode. As already noted this gives the effective zero, as conditioned by contact potential differences, which may vary from time to time with the amount of absorption of the alkali metal by the soot covered anode. Fig. 8 (a) shows a pair of voltage-current curves for monochromatic light of wave-length 4358 taken with $\perp$ and $\parallel$ light. Fig. 8 (b) shows a similar pair taken three weeks

later after the soot coating had absorbed enough alkali metal to shift the saturation point, but not enough to produce a current in the reverse direction for + voltages. These are representative of the kind of curves taken frequently during the course of the investigation to determine the effective zero. A point of considerable importance is immediately evident on inspection of Fig. 8 (b) where the curves are plotted as percentage of saturation current value. *This is that the curves for ⊥ and ∥ light are identical in shape.* The maximum energy of emission of photoelectrons is the same for both and the distribution of initial energies is the same. This is in agreement with the recently published work of Wolf.[9] The dashed curves are the derivatives, showing the numbers of electrons emitted at various initial energies. While the curves shown were obtained from deep pools of alloy, exactly similar curves are obtained from the thin film cells, in which the layer of alkali metal is only a few atoms thick at most. These curves closely approximate to the parabolic law assumed in the previous theoretical study. The

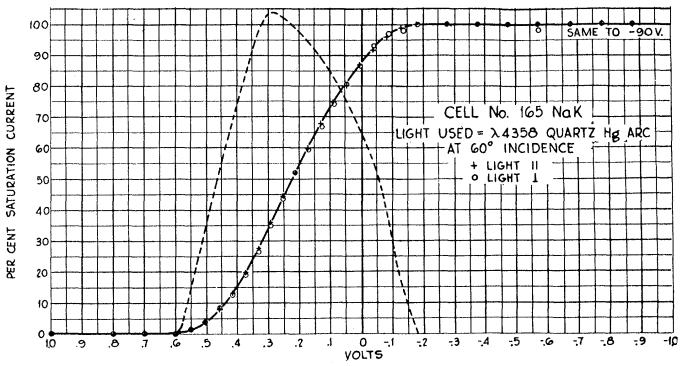

Fig. 8 (b). Voltage-current curves taken a few weeks after cell was made. Compare Fig. 8 (a).

distribution according to velocity is clearly not the Maxwell distribution frequently assumed in theoretical discussions.

The conclusion that the voltage-current curves are alike for ∥ and ⊥ light, is subject to qualification under certain experimental conditions. It has been a matter of frequent observation in our work that it is difficult to secure good saturation when using exciting light of long wave-length, i.e., near the photoelectric threshold. It has further been found that when this difficulty of attaining saturation is encountered, it is greater with ⊥ than with ∥ light. As the result of many experiments we have found that the occurrence of good saturation conditions for long wave excitation is definitely correlated with the completeness of the evacuation of the cells. In the type of cells here described, with their large soot coated surfaces, the necessary vacuum for complete saturation at zero fields is often attainable only by the use of liquid air on the attached charcoal tube; even so it is usually difficult to attain this condition for excitation by light near the photoelectric threshold, that is,

[9] Wolf, Ann. d. Physik **83,** 7 (1927).

for slow electrons. The behavior of a typical cell when excited by lights of various colors, is shown in Fig. 9. With blue light complete saturation is attained at zero field when the gas pressure is held to its minimum value by the use of liquid air on the charcoal tube. Without liquid air the discharge

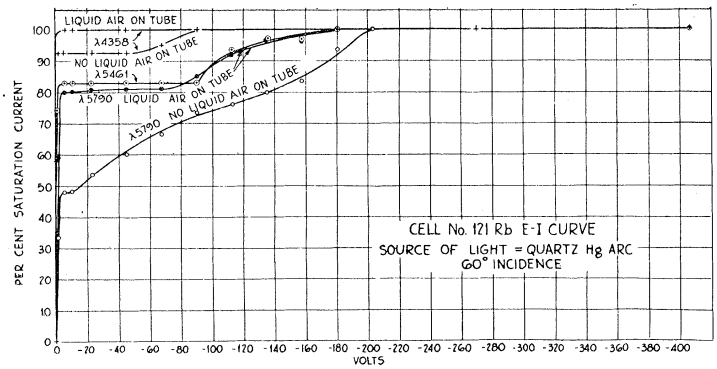

Fig. 9. Comparison of voltage-current curves for imperfect vacuum central cathode cell under illumination with monochromatic light of various wave-lengths. Note better saturation at low voltages with improved vacuum.

attains apparent saturation at zero field, but, at considerably higher voltages (50–60) the current again increases, slowly, to a new saturation value approximately 10 percent higher, which is unaffected by further increase of the field (at least up to 400 volts). The same type of behavior is shown under excitation by green and yellow light, except that the difference between the first (apparent) and second saturation values is greater, and that, in the case

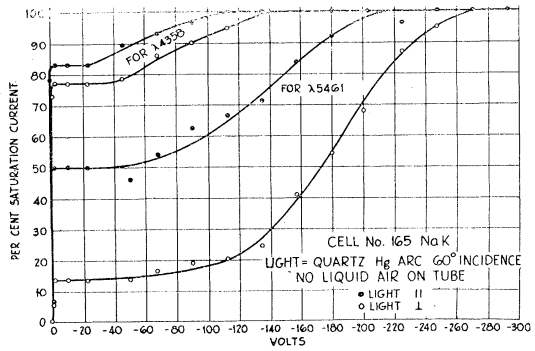

Fig. 10. Voltage-current curves for imperfect vacuum central cathode cell for ∥ and ⊥ light showing poorer saturation for ⊥ light.

shown, it is not possible even with liquid air to attain a vacuum sufficient to eliminate the second rise of current.

In Fig. 10 are shown data for ⊥ light and ∥ light in a cell without liquid air, for two wave-lengths of exciting light. The outstanding fact here is that,

as *judged by the saturation phenomena, the* ⊥ *light behaves as though it were of greater wave-length than the* ‖ *light.* Another feature of the influence of small quantities of gas is that the ratio of emissions (‖/⊥) is much greater for the low voltage saturation than for the high. This is exhibited again in Fig. 11 where the ‖/⊥ ratio changes from approximately 8:1 at zero volts to approximately 2:1 for 4 volts and above. Students of photoelectricity will recognize in Fig. 11 precisely the kind of curves obtained by Lenard[10] who ascribed the knick to a surface layer. Later work[11] has been interpreted as proving this corner at low voltages to be due to reflected electrons, but the dependence on gas pressure here shown is more in accord with Lenard's view.[12]

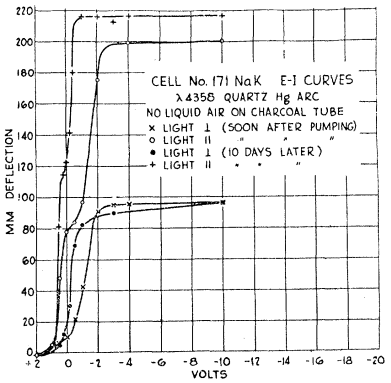

Fig. 11. Voltage-current curves for imperfect vacuum central cathode cell, showing poor saturation effect extending over voltage range of approximately 2 volts. Compare with Figs. 9 and 10.

We are not prepared to offer a detailed explanation of these effects of residual gas on the voltage-current curves. The curves of Fig. 9 are in general what might be expected if the surface were spotted with areas covered with gas to a considerable thickness. Such spots of gas would retard the slower electrons emerging from the metal surface beneath them more than the fast electrons, but the application of strong fields would ultimately pull the electrons through the retarding layer. According to this theory the initial saturation currents arise from the clean areas between the gas covered spots. If the data of Fig. 10 are to be interpreted as showing that the ‖ electrons are faster than the ⊥ then this is a property they possess only when the surface is gas covered, for as already shown by the data in Figs. 8a and 8b the voltage-current curves for the two kinds of light show complete similarity for the gas-free surface. In view of the additional complexity of the phenomena with long wave excitation in the presence of residual gas we have purposely restricted the present study to the conditions of high vacuum and short wave excitation, these being fortunately at the same time the conditions for the most definite exhibition of the differences of emission under ⊥ and ‖ light.

[10] Lenard, Ann. der Physik **8,** 149 (1902).

[11] Ladenburg and Markau, Ver. d. Phys. Ges. **10,** 562 (1908).

[12] The defects of saturation shown in Figs. 9 and 11 explain results obtained in certain earlier investigations. Thus in a study of central anode cells (Ives and Fry, Astrophysical Jour. **56,** 1 (1922)) it was found that the curves for "red" and "blue" light were not separated so far as the theory would indicate. It now appears that this was due to the relatively poorer saturation of the "red" current in the presence of residual gas. Again the announcement of a lower energy of emission for ⊥ electrons (Ives, Phys. Rev. **21,** 713 (1923)) was a misinterpretation of curves similar to those of Fig. 11, which, particularly in the presence of a "tail" of emission from the anode appear like similar curves shifted laterally by nearly a volt.

The next set of data in order for consideration are the voltage-current curves for individual tabs or collectors at various angular positions with respect to the cathode. In Figs. 12, 13, 14 and 15 are shown a set of curves

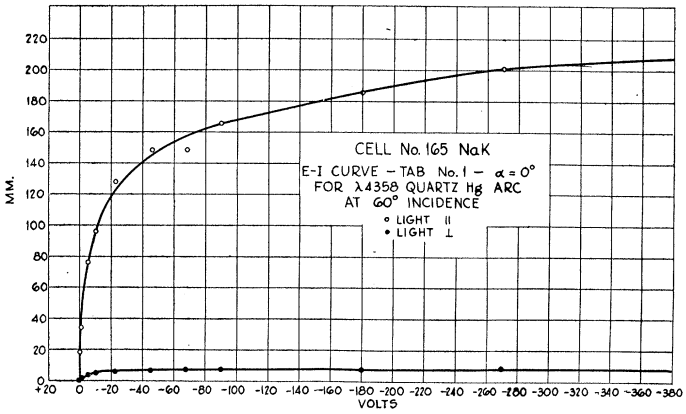

Fig. 12. Voltage-current curve to collector at normal to surface ($\alpha = 0°$).

for tabs at angles of 0°, 30°, 60° and 90°, which are representative of a great many obtained in the course of the investigation. The characteristic feature of the voltage-current curves for tabs at high angles to the normal is that the current rises quickly to a maximum for very low voltages and then declines,

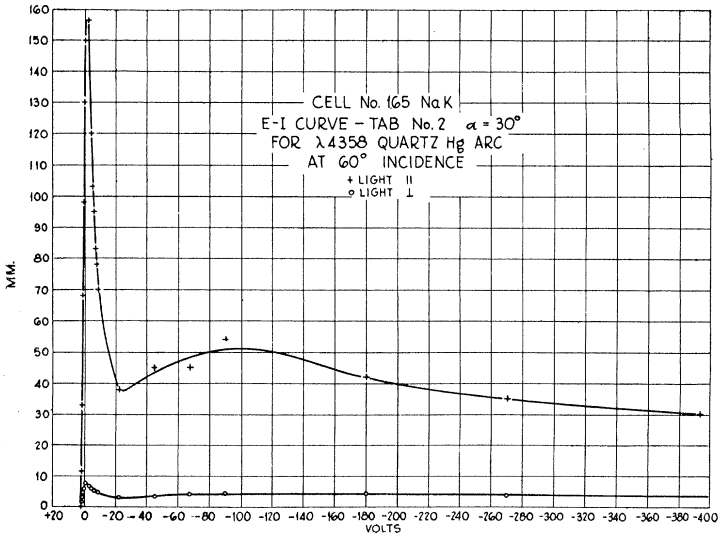

Fig. 13. Voltage-current curve to collector at 30° to normal ($\alpha = 30°$).

in excellent agreement with the calculated curves of the theoretical paper previously referred to. This agreement is in fact sufficiently close, as is shown by Figs. 16 and 17, to indicate that the underlying assumptions as to direction

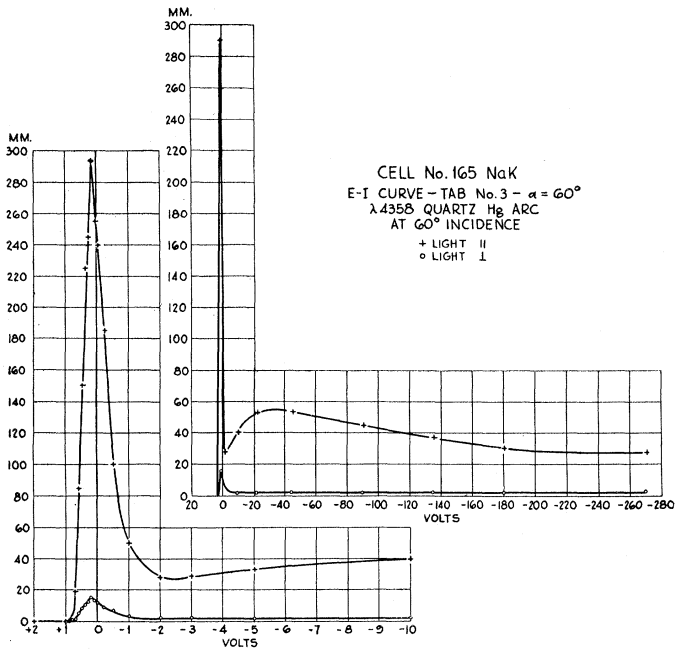

Fig. 14. Voltage-current curve to collector at 60° to normal ($\alpha = 60°$). Same curve plotted on two scales.

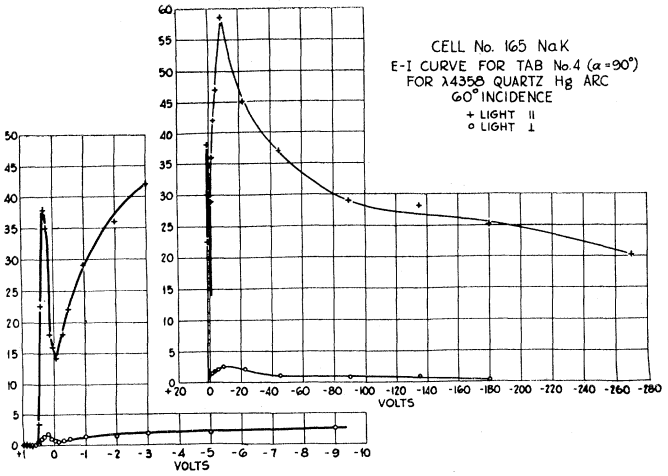

Fig. 15. Voltage-current curve to collector at 90° to normal ($\alpha = 90°$). Same curve plotted on two scales.

and velocity distribution used in the theoretical study must be very near the truth. It will be noted that in general the maximum current falls at the correct voltage and that the shape is closely similar to that given by the theory. Some of the differences which appear between the experimental and calculated curves are such as may be explained by the difficulty in determining the exact angle to be assigned to a finite tab, others to the finite size of the illuminated spot. The data shown in Figs. 16 and 17 suggest that there is an excess of high energy electrons at small angles to the normal and a deficiency at high angles. It is to be noted, however, that these observations

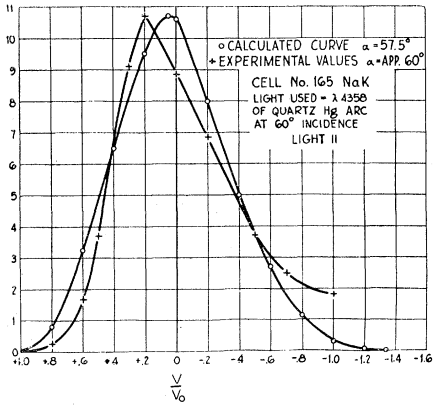

FIG. 16

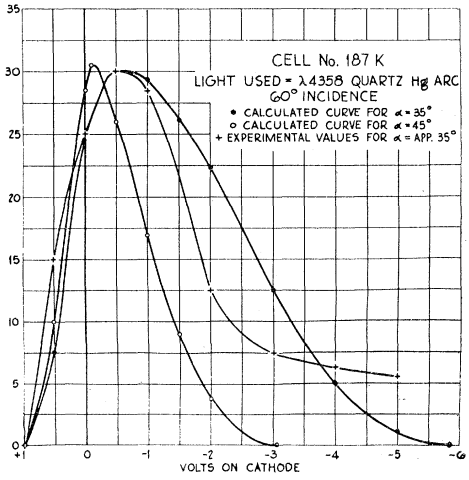

FIG. 17

Fig. 16. Comparison of calculated and experimental voltage-current curves for collector at 60° from normal to cathode. Failure to agree at peak is as expected since computed values (taken from preceding paper) are for slightly smaller angle.

Fig. 17. Comparison of calculated and experimental voltage-current curves for collector at approximately 35° from normal to cathode. Note how slight increase in size of angle moves curve to left.

were on flat electrodes, instead of the spherical one assumed in the calculations, so that exact agreement is not to be expected. Considering all our experimental data we find no sure evidence that the energy distribution differs for different angles of emission. This is of course a question which could be answered by experiments with other types of cells designed specifically for the purpose.

There is, however, a feature of these curves which is not in accord with the theory, and that is the behavior at higher voltages. Instead of falling as predicted to zero at some relatively low voltage, the emission approaches zero, rises to a second maximum and then again declines very slowly toward the highest voltages studied. This emission at higher voltages was the subject of very considerable study during the course of this work. It was at

first thought it might be a characteristic of the flat plate cathodes used in our earlier cells instead of the spherical cathodes assumed in the theoretical study. This led to the construction of several cells with a polished spherical platinum cathode on which the alkali metal was sublimed, as illustrated in Fig. 1. These cells gave exactly the same type of curves as the flat plate cells. It was then thought possible that the high voltage emission was caused by the platinum surface, in spite of its high polish, not being as perfectly specular as for instance a liquid sodium-potassium alloy surface. It was also thought possible that it was due to scattered light falling upon other parts of the electrode. To test these possibilities, cells were made up with a cup into which liquid sodium-potassium alloy was allowed to flow, and one of these cells was made with side tubes, one carrying the glass window to a considerable distance from the cathode, the other acting as a trap for the reflected light as previously described (Fig. 2).

The high voltage emission persisted in spite of these changes of design. As a result of our work we have, however, established that the unpredicted emission at high voltages is proportional to the principal electron emission as found, in agreement with prediction, at low voltages. This is shown by Figs. 13 and 15 in which the two curves for light in the $\parallel$ and $\perp$ planes are practically directly proportional to each other at all points. If the unpredicted emission were due to scattered light it would be substantially the same for $\perp$ and $\parallel$ light. We conclude from this proportionality that the high voltage current is due to secondary emission of electrons from the anode, as a whole, to the collecting tab. The shape of the voltage-current curve is in general agreement with this idea. For, as the voltage is increased from zero and electrons strike the anode at higher speeds, we would expect an increase of the secondary emission. On the other hand, with increasing field the primary electron stream is pulled more and more toward the normal to the surface, thereby restricting the emission of secondaries to a smaller spot on the anode, farther distant from the high angle collecting tabs. Due to this focussing of the primary emission we should expect a decrease in the number of secondaries striking the high angle tabs, and this decrease should set in earlier the higher the angle of the tabs. This is just what occurs, the maximum for the secondaries moving from 8 volts for the 90° tab to 100 volts for the 30° tab.

For our present purposes this secondary emission, once recognized as such is of no great importance, since in order to determine the distribution-in-direction it is only necessary to work at voltages of zero or less, where the secondary emission is negligible. Even were it appreciable, the fact that it is apparently directly proportional to the low voltage emission which we deem primary would tend to cancel its effect on our significant measurments.

Before passing on to the next type of data, we note that according to Figs. 12–15 there is no apparent difference in the character of the emission due to the $\parallel$ and $\perp$ kinds of illumination, when measured to individual tabs.

We are now ready to consider the direction distribution data, represented as to their general character by the ellipses of Fig. 7.

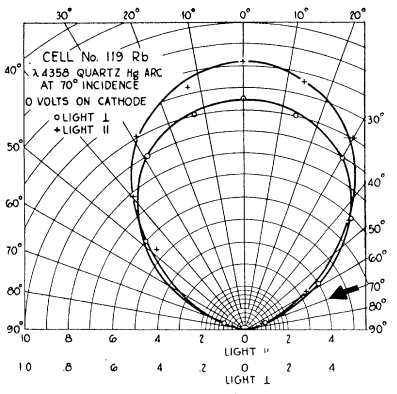

Fig. 18. Symmetrical angular distribution curve showing no tendency for electrons to follow electric vector of polarized light. Arrow shows direction of incidence of light.

The question of greatest interest perhaps with regard to these distribution curves is whether they reflect in any way the direction of the electric vector, as appears to be the case with photoelectrons produced by x-rays. In Fig. 18 are exhibited curves made with an exploring finger cell such as Fig. 1. In this the exposed end of the exploring finger rotates in an arc in the plane of incidence of the light, so that with obliquely incident light, if there is any following of the direction of the electric vector, the distribution curve should show a pronounced tilt for ‖ light and no tilt for ⊥ light. *Examination of these curves shows that there is no evidence of inclination of the ellipses.*

When this result was thoroughly established by a number of trials some study was made of the optical properties of metals to get an idea how much or how little tilt might be expected if the emission was due to light which had penetrated into the metal. The results of this study, which was made by Mr. T. C. Fry, are embodied in a recent paper by him.[13] In Fig. 17 of that paper will be found graphically represented the nature of the vibrations of the electric vector inside the metal. It appears that in all cases the ellipse by which the vibrations are represented is oriented with its major and minor axes very nearly tangential and normal to the boundary respectively, no matter how great the angle of incidence of the light. It might therefore not be considered surprising that the photoelectric emission shows no dissymetry with obliquely incident light.

It is however evident from Mr. Fry's work that if plane polarized light is *incident perpendicularly* on a metal surface, the electric vector keeps its direction unchanged in the metal. Consequently if when the plane of polarization is rotated the electron emission has a tendency to follow the electric vector, the ellipses of Fig. 18 should be much flatter when the electric vector is in the plane of collecting finger or tabs than when at right angles thereto.

This point was then tested experimentally. Light was incident on a sodium-potassium alloy surface in a perpendicular direction with the axis of the polarizing prism turned first to be parallel with the plane of the collector tabs and then at right angles thereto.[14] All the tabs were small and of the same size

[13] Fry, J.O.S.A. **16,** 1 (1928).

[14] This is our only experiment in which the ⊥ light was passed through a polarizing prism.

for the cell used. The observed points are given in Fig. 19. These show that *there is no difference whatever in the shape of the curves as the plane of polarization is turned.* The conclusion must therefore be drawn that in photoelectric emission from the alkali metal surfaces tested there is no tendency for the photoelectrons, after leaving the surface, to follow the electric vector. *All the direction-of-emission curves obtained are symmetrical about the normal to the surface.*

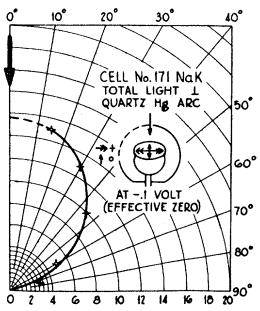

Fig. 19. Angular distribution curves for electrons emitted by polarized light at normal incidence. Result identical with electric vector of light parallel to and perpendicular to plane of collecting tabs. Small arrows show direction of light vector.

A practical advantage was taken of this result to build certain of the subsequent cells with the collecting tabs most distant from the normal several times the area of those near the normal, thus increasing the otherwise very small currents and securing greater accuracy in the measurements (Fig. 2).

Having disposed of this interesting question we may now examine in detail the distribution-in-direction curves, considering first their general shapes, and secondly the differences actually produced by changes in the nature of the illumination. It is first of all clear that the ellipses drawn through the experimental points in Figs. 5, 7 and 18, thus far referred to, are of the general shape called for by Lambert's law, previously assumed in our theoretical treatment. We may go further than this, however. If we examine Figs. 18 and 24 we find that in each case the ellipse for excitation by ⊥ light is *accurately that called for by Lambert's law.* That is, in Fig. 18 where the cathode is a sphere concentric with the anode, the ellipse for ⊥ light for zero field is slightly longer in the direction normal to the surface, just as it should be according to the calculations of the previous paper, which were made for a cell of this type. As pointed out, the true distribution (circle) would only be obtained for a small retarding potential. Again, in Fig. 24, where the cathode is a flat surface, with the emitting spot accurately in the center of the spherical anode, the curve for ⊥ light is *accurately a circle.* While there are experimental curves for ⊥ light among those shown subsequently, which are not exact circles for zero field, these were obtained under conditions where the exact determination of the effective zero field was not in question, or where the plane of the cathode was not so exactly central as in the cases shown. Hence we believe our data support the view that *Lambert's law is followed by the emission excited by ⊥ light.*

We may now consider the differences in the emission curves, as the angle of incidence and plane of polarization of the exciting light are varied. Typical of our experiments on this point are the curves shown in Fig. 20, which are similar to a great number obtained with all the types of cells described for

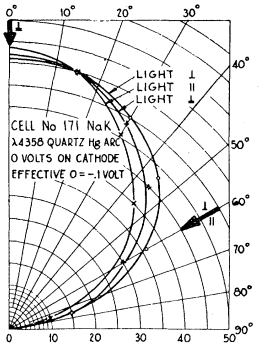

Fig. 20. Angular distribution of photoelectrons. Curves for light ||, ⊥, $\underline{\perp}$. Effective zero $= -0.1$ volt, so cathode voltage for these curves $= +0.1$ volt.

$\underline{\perp}$, || and ⊥ light. They differ in that, regarded as ellipses, the || curve is the most eccentric (longest axis normal to surface), and the ⊥ curve the least eccentric of the three, the $\underline{\perp}$ curve being intermemediate. The differences exhibited are indeed such as would be caused by a very small difference in the applied voltage, as is shown by Figs. 21 and 22, distribution-in-direction curves for various small retarding and accelerating potentials are plotted. (These are arbitrarily reduced to the same maximum value in order to exhibit the differences in shape more clearly.)

It is a matter of considerable importance to know whether the characteristic difference in shape for ⊥ and || light is a function merely of the angle of incidence and plane of polarization of light or whether it is related to the actual ratio of emissions for the various optical conditions. In order to determine this point, it is necessary to have distribution curves for surfaces in which the ratio of emissions varies over a wide range. We have had no difficulty in the present study in producing surfaces in which the ratio of emission for || and ⊥ light is as high as 20 to 1. We have, however, met with considerable difficulty in securing low ratios of emission. According to a

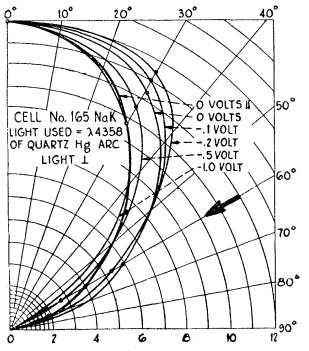

Fig. 21(a). Angular distribution of photoelectrons for light ⊥ with slight retarding potentials.

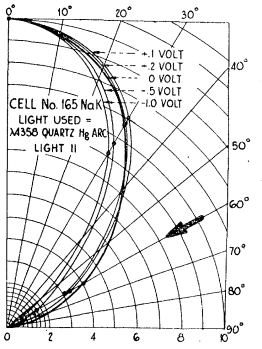

Fig. 21(b). Same as Fig. 21 (a) but for light ||.

previous study[6] it should be possible, by choosing the relative proportions of sodium and potassium in the alloy to secure liquid alloys in which the ratio of emissions was as low as 2 or 3 to 1. Actually we have had very poor success, for the reason that alloys so prepared and exhibiting low ratios when measured in a side tube, would assume very quickly a relatively high ratio when subsequently flowed into the cup in the main tube. This we believe

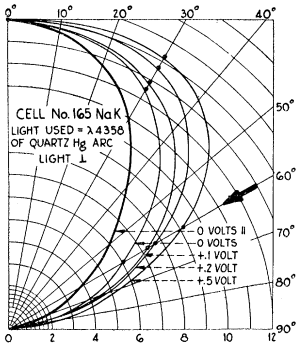

Fig. 22 (a). Angular distribution of photoelectrons for light ⊥ with slight accelerating potentials.

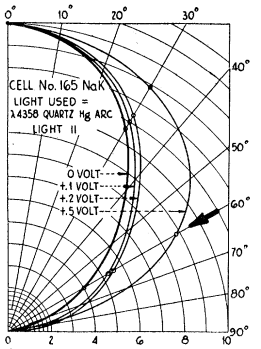

Fig. 22 (b). Same as Fig. 22 (a) but for light ||.

to be due to the fact that it has never been possible in these large cells with their soot-coated anodes to secure and maintain the extremely high vacua which are necessary to prevent some contamination of the surface. As Fleischer[15] has shown, a pure potassium surface which initially has a low ratio will take up sufficient hydrogen from the walls of a supposedly well exhausted vessel to develop a relatively high ratio.

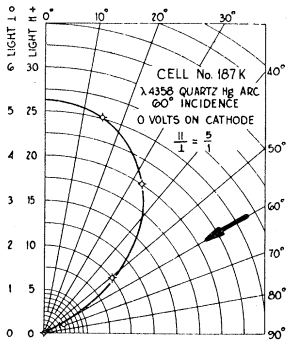

Fig. 23. Angular distribution of photoelectrons at 0 volts for pure potassium.

Our best data referring to a low ratio surface were obtained from a cell in which the cup was filled with pure solid potassium, which was allowed to cool slowly so that it developed a specular surface. In Fig. 23 the data for this cell, for which the ratio emissions for || and ⊥ light was 5 to 1, are shown by the circles and crosses. The two curves in this case coincide in shape. Also in Fig. 24 are shown the data for a cell in which the ratio was of intermediate value, namely 19 to 1. The ellipses in this case are well separated, while in the curves of Fig. 25 for a cell in which the ratio was 23 to 1, they are still further apart. It must be recorded, however, that we cannot consider these data entirely satisfactory in view of the fact that the potassium surface, while specular, was somewhat uneven and not comparable in character with the liquid alloy surfaces. It is possible that the surface was sufficiently rough so that the coincidence of the curves for ⊥ and || light is after all, in part at least, due to the occurrence of some || excitation under all conditions. Such data as we have on this point appear to be consistent with the view that the increasing eccentricity of the ellipse representing the distribution-in-direction is a function of the ratio

[15] Fleischer, Ann. d. Physik **82,** 243 (1927).

of emissions for ⊥ and ∥ light but the data are not as full or conclusive as we could wish.

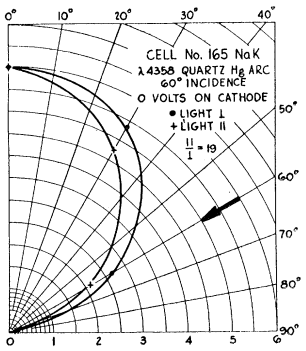

Fig. 24. Angular distribution of photoelectrons at 0 volts for Na K alloy. Ratio $\parallel/\perp = 19$.

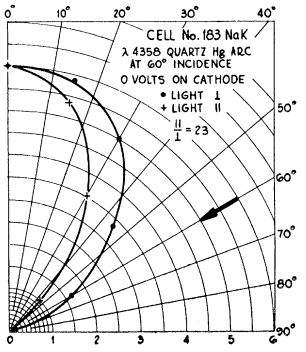

Fig. 25. Angular distribution of photoelectrons at 0 volts for Na K alloy. Ratio $\parallel/\perp = 23$.

Discussion of Experimental Results

The outstanding experimental results may be summarized as follows:

1. The distribution of photoelectrons in direction closely follows Lambert's law, the approximations being closest for excitation with obliquely incident light, with the electric vector parallel to the surface.

2. The distribution is under all conditions of illumination symmetrical about the normal to the surface.

3. The emission is more concentrated toward the normal for normally incident light than for obliquely incident light when the electric vector is parallel to the surface. The emission is still more concentrated toward the normal to the surface when, with obliquely incident light, the electric vector is parallel to the plane of incidence.

Another result is not so clearly established but may be stated as probable, namely:

4. The relative concentration of the emission toward the normal to the surface for obliquely incident light polarized in the two principal planes increases as the ratio of emission of photoelectrons for the two kinds of illumination increases.

It is now proper to attempt some explanation of the experimental findings in terms of the electrical or optical factors involved.

Any correspondence between the direction of emission, and the direction of the electric or magnetic vectors of the exciting light appears to be ruled out by our experiments. The close approximation to Lambert's law is most simply explained by assuming an entirely random direction of emissions within the metal, with a sufficient density of emitting centers so that the number passing through an element of surface in any direction will be as the projected area of the element in that direction. The explanation of the deviations we find from Lambert's law are then to be sought in some superposed or distorting effect, characteristic primarily of the surface, rather than of the exciting light.

One characteristic of the surface, deserving of consideration, is its work function. This might conceivably be altered by the character of the exciting light. As already stated, the differences in the direction distributions for $\underline{\perp}$ $\perp$ and $\parallel$ illumination are exactly those which would occur if the applied field differed in the several cases. As is shown by Figs. 21 and 22, a difference of a few tenths of a volt would suffice. In the case of gas contaminated surfaces (Fig. 10) a very considerable difference of voltage is actually required to release the second saturation electrons due to $\parallel$ and $\perp$ light, lending weight to the idea that a surface presents different opposing forces under the two conditions. However, for the case we are here concerned with, surfaces in the gas-free condition, the voltage-current curves for the total $\perp$ and $\parallel$ currents in Fig. 8, which are identical, give no support for an explanation calling for different effective fields in the two cases.

A second characteristic of the surface is its relative absorptive power for light incident at various angles and planes of polarization. Curiously enough —for it is difficult to interpret its significance—the one apparently complete correlation shown by our work is between the eccentricity of the ellipses representing the distribution-in-direction and the relative photoelectric emissions for the various illumination conditions. Thus the smallest emission is for $\perp$ light, the greatest for $\parallel$ light, with an intermediate emission for $\underline{\perp}$ light. In the case of $\perp$ and $\underline{\perp}$ light the emissions are practically as the absorption of light by the alkali metal. In the case of $\parallel$ light the emission is out of proportion to the absorption, as ordinarily measured, for infinitely thick layers, but may be proportional to the intrinsic absorption of a surface layer, peculiar to the occurrence of the "selective" effect. The correlation here pointed out is therefore probably between eccentricity and absorptive power. We have, however, been unable to find, by study of the optical properties of metals[13] any difference in the behavior of the differently absorbed kinds of light, such for instance as depth of penetration, which offered any clue to the meaning of this correlation. This correlation, it may be pointed out, is exactly opposite to that which would be exhibited by the surface if emitting thermal radiation. In that case, if the emitted radiation were examined in different directions, and for different planes of polarization, the deviations from Lambert's law would be in the opposite order.

Gardner in the paper referred to previously develops the idea that the photoelectrons, initially ejected in all directions equally, suffer absorption or loss according to the distance traversed in reaching the surface. This picture leads to a distribution-in-direction substantially according to Lambert's law. It further indicates that the greater the depth at which the electrons originate the more the emission will be concentrated toward the normal. If this theory were accepted the differences exhibited under $\underline{\perp}$, $\perp$ and $\parallel$ illumination could be explained by supposing that the average depth from which the electrons are extracted varies with the character of the light, being greatest with $\parallel$ light.

Against this view several objections may be raised. In the first place, as already noted, the electromagnetic theory of the optical properties of metals

does not permit of any significant difference in "depth of penetration" for the several kinds of light. In the second place, there is evidence[16] that the photoelectrically active layer is at most only a few atoms thick (<5), a depth at which optical absorption is insignificant. Another objection to the theory is that it pictures the electrons as continuing their initial direction of emission both inside and outside the metal, in spite of the encounters to which their diminution in numbers is ascribed. In other words, the electrons must be assumed either to emerge without any deflecting encounters, or to be completely stopped by every encounter. The distribution of electrons according to energy, which has often been ascribed to velocity losses after several collisions, would have to be assigned to some other cause, since such collisions would probably alter the paths of the electrons as well.

Disregarding for the moment the seriousness of these objections it is of interest to note that the differences in depth of penetration, i.e., in optical absorption, for $\perp$, $\parallel$, and $\underline{\perp}$ light called for if we assume the observed differences in emission to be due to this cause, are similar to those exhibited by a plate of tourmaline cut at right angles to its optic axis. While the structure of tourmaline is not known, it is probable that its markedly different absorption for light polarized parallel and perpendicular to the optic axis is due to a regular arrangement of atoms with very different spacings in different planes.

An alternative assumption to that of different depths of penetration is that there are present several kinds of atoms or atom groups, certain of which are capable of ejecting more electrons normally to the surface than others, and that these particular atoms or groups are at the same time more easily excited by $\parallel$ than by $\perp$ light. This assumption does not commit us to any simple relation between the direction of the electric vector and the direcl tion of electron emission, and is thus far in agreement with our experimenta- findings. It offers, however, no explanation of the intermediate character of the emission under normally incident light ($\underline{\perp}$).

While we have not been able to formulate a satisfactory theory for the distribution-in-direction phenomena we have observed, one common feature of the partial hypotheses just outlined appears to be inevitable in all attempted explanations of normal and selective effects. This feature is the assumption of some form of anisotropy of the surface, whereby it is distinguished from the isotropic or amorphous structure which ordinary measurements of the optical properties of the alkali metals indicate, and on which the calculations of absorption, reflection and other optical properties are ordinarily based. The fact that the photoelectric emission is due to an extremely superficial layer of atoms allows us to ascribe the peculiar properties under discussion with considerable confidence to some special arrangement of these atoms, even though the exact nature of this arrangement eludes us.

BELL TELEPHONE LABORATORIES, INC.
February 7, 1928.

[16] Ives and Johnsrud, J.O.S.A. & R.S.I.

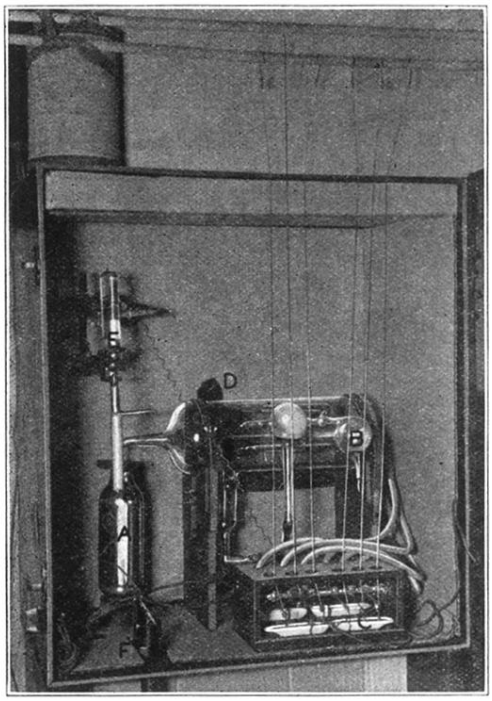

Fig. 4. Photograph of a photoelectric cell in place. *A*, liquid air flask on charcoal tube; *B*, small photoelectric cell connected with large one to permit study of relative emissions for light $\parallel$ and $\perp$ before pouring alloy into cathode stem of large cell (Fig. 2); *C*, switching device whereby each tab of cell (Fig. 2) can be disconnected from ground and connected to the electrometer in turn by pulling proper silken thread leading out through top of shielding box; *D*, lens and prism unit through which light was admitted; *E*, xylol-alcohol resistance across electrometer; *F*, carefully insulated and shielded wire leading to electrometer.