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The Absolute Photoelectric Yields of Mg, Be and Na

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Measurements of the absolute photoelectric yields for distilled surfaces of Mg, Be and Na were made and values of α in Fowler's photoelectric equation determined. For Mg, Be and Na the values of the work function are, respectively, 3.68, 3.92 and 2.29 volts and of α, 3.2, 25 and 180×10^{-34} cm^2 sec./quant. These values of α range from 10^{-2} to 10^{-3} of the maximum theoretical values. The ratios are interpreted as the fraction of light absorbed by the electrons in the surface potential barrier.

INTRODUCTION

FOWLER'S theory of the surface photoelectric effect in metals leads to the following equation[1] for the saturation current I excited by unit intensity of incident light of frequency ν,

$$I=\alpha A T^2\varphi(x), \tag{1}$$

where $\varphi(x)$ is a universal function of the quantity $x=h(\nu-\nu_0)/kT$, A is the thermionic constant having the value 120 amp./cm^2 deg.^{2} and α is a proportionality constant involving the probability of light absorption by electrons at the surface. Repeated experimental tests have shown this equation to hold quite accurately for reasonably wide frequency ranges in the vicinity of ν_0. It is evident, therefore, that within the frequency range for which the equation is valid, the photoelectric emission from any surface may be fully specified by giving the values of the two constants ν_0 and α, which are quite analogous to the constants b and A in the Richardson thermionic equation. Fowler's method has now become standard for the determination of photoelectric thresholds but very little attention has been given to the absolute values of α. It was the purpose of this investigation to determine values of α for various surfaces and for a single surface under various conditions.

As has been pointed out by one of us,[1] simple considerations allow one to set an upper limit to the value of α for any surface and these considerations also suggest that unless additional factors enter, the values of α for different surfaces should not be widely different. Thus if it is assumed that all incident quanta are absorbed by electrons bound within the surface potential barrier the value of α should be

$$\begin{aligned}\alpha&=(2m/\pi h)(8\pi/3n)^{4/3}\\&=15.1n^{-4/3},\end{aligned} \tag{2}$$

where n is the number of free electrons per unit volume, and the unit of light intensity is taken to be 1 quantum/cm^2 sec. Since, however, the electrons bound in the surface field occupy a layer of only atomic dimensions and since the light penetrates into the metal a distance of the order of its wave-length one would expect that the fraction of the light absorbed by the surface electrons would be from 10^{-2} to 10^{-3} of the incident light. The ratio of the observed value of α to the value calculated from Eq. (2) might then be taken as a measure of this fraction.

It should be stated, of course, that as more exact theories of the photoelectric effect are developed the exact interpretation of the quantities entering Eq. (1), which is certainly a good first approximation, may be changed. Nevertheless, these qualitative ideas aid greatly in interpreting results and from the experimental point of view a study of the values of α is of great importance.

A further remark should be made in regard to the units in which the I of Eq. (1) is to be expressed. In the present paper I has been expressed in electrons/quantum rather than in amp./watt or other intensity units used in previous work. This is because in these units the value of α has a clearer interpretation and also because the whole theory is based on the quantum picture. Actually, however, we can detect no systematic differences in the fit of the data to

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[1] See L. A. DuBridge. *Actualités Scientifiques et Industrielles*, No. 268 (Hermann and Cie, Paris, 1935).

the theoretical curve whichever units are used, except for slight differences in the threshold ν_0 and, of course, in α. Cashman and Jamison[2] have recently come to the same conclusion though in their experiments the frequency range was such that the value of x ran up to only about 18, while our experiments extended up to $x=50$. Fig. 4 shows the fitting of data reduced both to amp./watt and to electrons/quantum. In this case the values of ν_0 for the two curves differ by 0.03 volt or by about 0.8 percent.

PROCEDURE

The metals used in this investigation were beryllium, magnesium and sodium, chosen mostly for their interest in connection with other work in progress here and elsewhere, and also because the work functions were sufficiently low to allow a fairly wide range of frequencies to be used. The very careful vacuum technique found necessary in previous photoelectric work was followed throughout to secure surfaces as free from contamination as possible. All of the metals were distilled in vacuum onto a glass or metal surface in the form of an opaque layer. When distillation of successive layers caused no change in photoelectric emission this was taken to mean that the surface was clean, or at least in a stable condition.

The beryllium cell is shown in Fig. 1. The beryllium was held in a small spiral filament E which was coated with an insulating clay. It was evaporated, by heating of the filament, on to the inner surface of the metal cylinder C. The central tungsten filament F served as the anode. The opening of the cylinder and the quartz window Q were oriented in such a manner that the incident light suffered at least two or three reflections, thereby insuring the absorption of a large fraction.

For magnesium a cell of the double distillation type was used and is shown in Fig. 2. The magnesium was enclosed in a small molybdenum box M, open at the front. Immediately behind it was a filament F of 10 mil tungsten which was used to heat the magnesium. From this point the magnesium was evaporated on to the nickel disk N which was then turned around by an external magnet and the magnesium was driven on to the spherical surface G by heating the disk by electron bombardment.

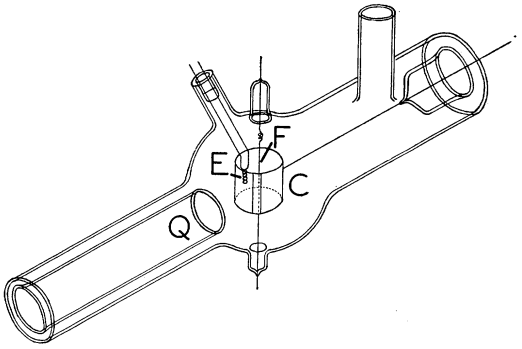

FIG. 1. Beryllium photo-cell.

The sodium cell is shown in Fig. 3. The sodium, which had been initially distilled in vacuum and sealed off in small Pyrex pellets, was placed in the side arm A. The tungsten filament F, in the form of a loop, served as the anode. The sodium was evaporated into the main bulb by heating the two parts of the side arm with furnaces. Continued distillation of the sodium for three or four days produced surfaces which gave reasonably reproducible results which are believed to be typical of rather clean sodium.

Each photoelectric cell was baked for several days at high temperatures. The metal parts were then thoroughly bombarded, and a second baking given the tube. The metal to be distilled was then heated to a temperature just below the

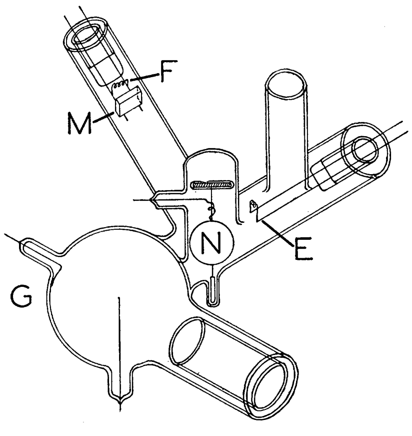

FIG. 2. Magnesium photo-cell.

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[2] R. J. Cashman and N. C. Jamison, Phys. Rev. 50, 568 (1936).

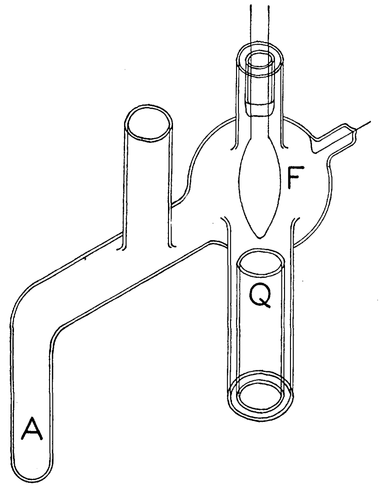

FIG. 3. Sodium photo-cell.

vaporization point for one to three days or until appreciable gas evolution had ceased. The temperature was then very slowly raised to the point where an opaque layer was deposited in about 10 hours. Further layers were laid down on the first after each series of measurements and additional check runs were made by cleaning out the cell and depositing new layers.

Energy measurements of the radiation emerging from the slit of the Bausch and Lomb quartz monochromator were made with a Bi-Te vacuum thermopile constructed by Mr. J. P. Foerst of the University of Wisconsin after the design developed by the late Professor Mendenhall. By subtracting both from the thermopile and the photoelectric measurements the average background radiation between spectral lines of the mercury arc, the effects of scattered light of other wave-lengths was effectively eliminated. In the measurements on sodium the continuous radiation from a projection lamp was used in addition to the mercury arc. In this case the slit widths were reduced to values so small that scattered light was unimportant, as was evidenced by the agreement between the arc and lamp data. The thermopile was calibrated in absolute units by a National Bureau of Standards standard lamp. In all cases the photoelectric cells approached the "black body" conditions so that practically all of the light incident was absorbed by the surface and no correction for reflection coefficients need be introduced.

RESULTS AND DISCUSSION

Typical Fowler plots for Mg, Be and Na are shown in Figs. 4, 5 and 6. The best values of the work functions and of α for clean surfaces of these metals are given in Table I:

The value of 3350A for the threshold of Mg is in reasonably good agreement with the value 3430 reported by Cashman and Huxford[3] for carefully prepared surfaces.

In the case of Be no previous measurements have come to our attention. Inasmuch as Dr. Zworykin, of the RCA Victor Company, informed us that Be sensitized with O_2 showed a rather high secondary emission we attempted to see whether such surfaces showed a high photoelectric yield. Short glow discharges in O_2 at low pressures, however, produced changes in threshold of only about 0.1 volt and a longer discharge at higher pressure desensitized the surface completely shifting the threshold to below 2200A. There was no evidence of a condition of low work function, though the possibilities were by no means exhausted.

The values found for the work function of Na by various workers are notoriously inconsistent.[4] The value found in this work for a distilled layer on glass was quite reproducible under the conditions of the experiment. It is in fairly good agreement with the theoretical value 2.35 volts, predicted by Bardeen,[5] and the value of 2.4 volts reported by Brady and Jacobsmeyer[6] for a thin film on Al. It will be noted, however, that the sodium data do not fit the Fowler plots over as wide a frequency range as for the other metals, a point which is being further investigated. This is shown also in Fig. 7 where yields are plotted against λ. For the other metals the data fit the theory for a range of x values of about 50, a much wider range than used in most previous experiments.

The relation between the observed values of α and the values calculated from Eq. (2) can be seen from Table II, in which are listed also values reported by other workers.

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[3] R. J. Cashman and W. S. Huxford, Phys. Rev. **48**, 734 (1935).

[4] See Hughes and DuBridge, *Photoelectric Phenomena*, p. 75.

[5] J. Bardeen, Phys. Rev. **49**, 653 (1936).

[6] J. J. Brady and V. P. Jacobsmeyer, Phys. Rev. **49**, 620 (1936).

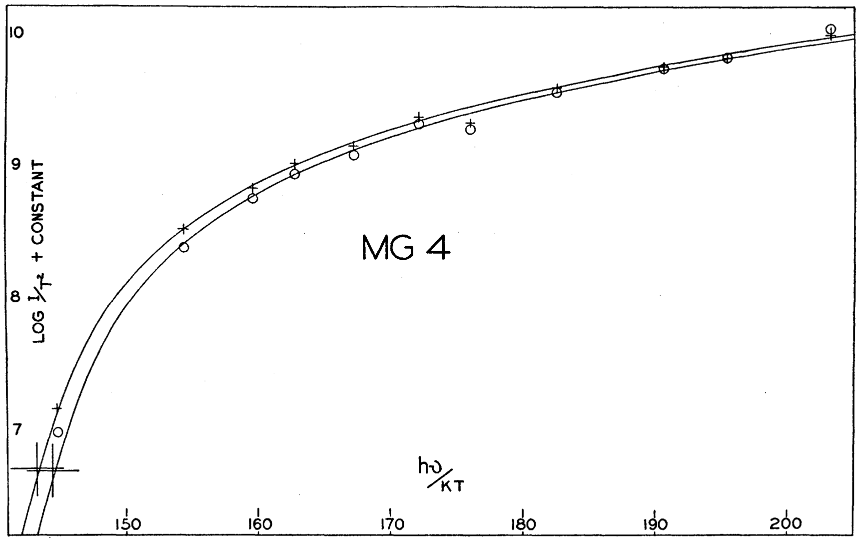

FIG. 4. Fowler plot for Mg. Upper curve, amp./watt, const. = 20, $\varphi = 3.65$ V. Lower curve, electrons/quant., const. = 19.3, $\varphi = 3.68$ V.

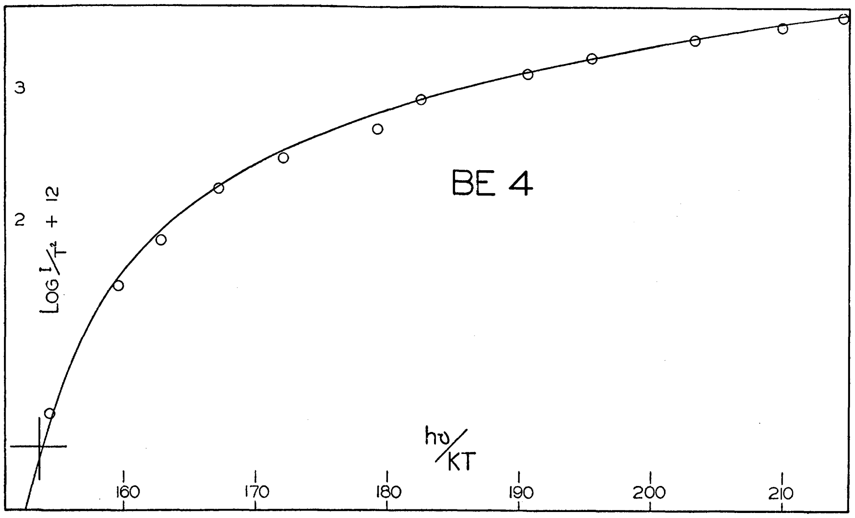

FIG. 5. Fowler plot for Be. elec./quant., $\varphi = 3.92$ V.

Table III shows the variation of α with contamination of the surface for Na and Be. In the

TABLE I. *Work functions and values of α, the probability of light absorption by electrons.*

Metal	φ Volts	λ_0 A.U.	$\alpha \times 10^{34}$ sec. cm^2 quant.$^{-1}$
Mg	3.68	3350	3.2
Be	3.92	3150	25.
Na	2.29	5390	180.

TABLE II. *Observed and calculated values of α.*

Metal	α(obs.) $\times 10^{32}$ sec. cm^2 quant.$^{-1}$	$\alpha \times 10^{32}$ calc.	Ratio calc./obs.	Ref.
Be	0.25	12.5	50	1
Mg	.032	48.8	1520	1
Na	2.29	198.	86.5	1
W	.026	29.4	1140	2
Ba	.43	140.	325	3

1. Present work.
2. A. King, unpublished.
3. Cashman and Jamison, reference 2.

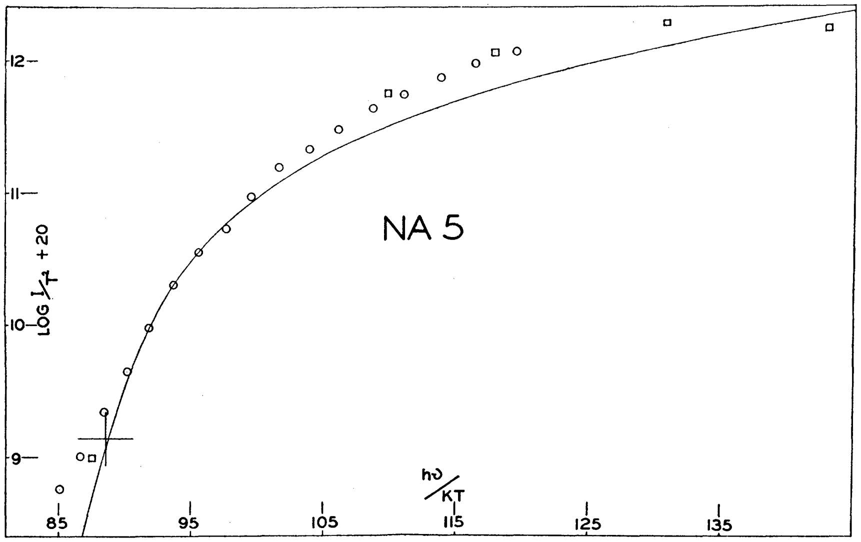

FIG. 6. Fowler plot for Na. $\varphi=2.29$ V.

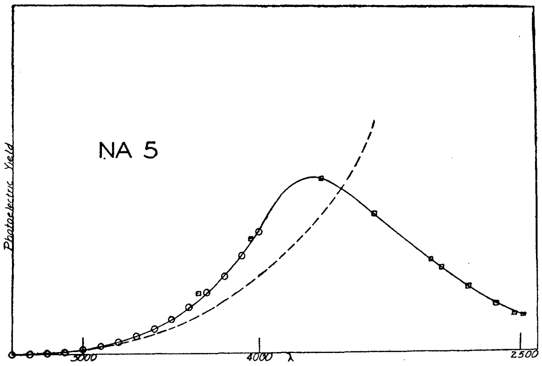

FIG. 7. Spectral distribution curve for Na. Dashed curve, Fowler's theory. ○ tungsten lamp, □ Hg arc.

case of Be the values represent the effects of successive glow discharge in O_2 and for Na the values are for successive layers laid down, the last being most free of gas contamination. These variations in α are relatively small and show no systematic trend.

TABLE III. *Showing variation of α with contamination.*

Metal	φ	α	α calc./α obs.
Be	3.92	17.9×10^{-34}	70
	3.89	7.0	178
	3.81	5.8	215
	3.81	4.6	262
	3.82	4.0	312
	3.92	5.7	219
Na	2.24	1.8×10^{-32}	110
	2.27	2.0	98
	2.29	2.0	98
	2.29	1.5	131

It is evident that the values of $\alpha_{\text{obs.}}$ lie in general between 10^{-32} and 10^{-34}. If we interpret the ratio obs./calc. as the fraction of light absorbed in the surface layer it is evident that this varies rather widely but lies in general in the range 10^{-2} to 10^{-3}. It is hoped that further developments of the quantum theory of photoelectric emission now being carried out in this laboratory will provide a theoretical basis for predicting the absolute values of photoelectric yields.

To compute the actual photoelectric emission in electrons/quantum at any wave-length for a surface for which ν_0 and α are known it is only necessary to use Eq. (1). Since this involves only the difference $(\nu-\nu_0)$ it is often convenient to compare the yields of surfaces for a given value of this quantity, or of x. Thus for $x=40$, $\varphi(x)=800$. Hence at 300°K we have

$$I_{40}=\alpha\times5.35\times10^{28}\text{ elec./quant.}$$

For values of α of the order of 10^{-33} then $I_{40}\cong5\times10^{-5}$ elec./quant.

In conclusion the authors wish to express their appreciation to Mr. R. J. Maurer who assisted in analyzing the data.