The ratio between two adjacent Sargent curves is about 100. It is not immediately possible to decide whether the improbability in the case of Li^8 is caused by spin changes, geometrical factors, or a combination of both.

The existence of a stable ground state for Be^8 would admit the possibility of β-transitions to the ground state without the emission of α-particles. Allison and co-workers[15] have recently reported that Be^8 is stable with respect to two α-particles by 0.31 ± 0.06 Mev. Rumbaugh, Roberts and Hafstad[6] found that the number of delayed α-particles from the Li^8 reaction is 1.1 times greater than the total number of β-particles observed. They suggest that various corrections would tend to increase the ratio of α to β. The ratio 1.1 : 1 may be regarded as setting a limiting value to the relative probabilities of β-decay to the continuum and to the stable state of Be^8. Beta-decay to the continuum will have to compete with decay to the ground state; this competition will decrease the values of the matrix elements as calculated above, which represent transitions to the continuum only, by a factor of 0.55. One obtains $|M_c|^2 = 0.10(L=0)$; $= 0.14(L=2)$.

The matrix element for transitions to the stable state can be estimated in a similar way. The direct estimate must be corrected for the spreading of the wave function of the ground state beyond the boundaries of the potential well. The ground state is assumed to consist of two α-particles with $L=0$. One gets finally $|M_s|^2 \leqq 0.04$. On the basis of this low value one might tentatively suggest that the excited state has $L=2$, and β-transitions to the ground state are forbidden by a strong selection rule.

It is a pleasure to thank Professor G. Breit for suggesting this problem, and for his constant advice. I am very indebted to Professor J. A. Wheeler for permission to use his calculations of phase shifts before publication. The Wisconsin Alumni Research Foundation has granted financial support.

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[15] S. K. Allison, E. R. Graves, L. S. Skaggs and N. M. Smith, Jr., Phys. Rev. **55**, 107 (1939).

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Total Secondary Electron Emission from Tungsten and Thorium-Coated Tungsten

EDWARD A. COOMES*
George Eastman Laboratories of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

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The secondary electron emission from polycrystalline tungsten covered with monomolecular films of thorium evaporated onto it from a thoriated tungsten filament, has been investigated over an energy range for primary electrons of 100 to 1000 volts. The state of the target surface was ascertained from thermionic emission measurements. For clean thorium on clean tungsten apparently the secondary emission coefficient did not change with thoriation for primary energies below 200 volts, but decreased at higher voltages with increasing amounts of thorium on the target. No observed increase in secondary emission takes place with a reduction in the work function of tungsten by a monomolecular layer of pure thorium; apparently there is a decrease in secondary emission in this case. When the thorium-coated tungsten was treated with oxygen released from the thoriated tungsten filament the work function increased, but there obtained also an increase in the secondary emission coefficient; further change in work function by evaporation of thorium caused a variation of the secondary emission coefficient that other experimenters also have observed.

INTRODUCTION

SYSTEMATIC studies of the secondary electron emission from composite surfaces bombarded with low energy primary electrons have been carried out by several investigators,[1–3] but conclusions reached are at variance. Data[2] are available which check a theory stating that

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* Now at the University of Notre Dame.

[1] Paul L. Copeland, Phys. Rev. **46**, 435 (1933).
[2] L. R. G. Treloar, Proc. Phys. Soc. **49**, 392 (1937).
[3] H. Bruining and J. H. de Boer, Physica **5**, 17 (1938).

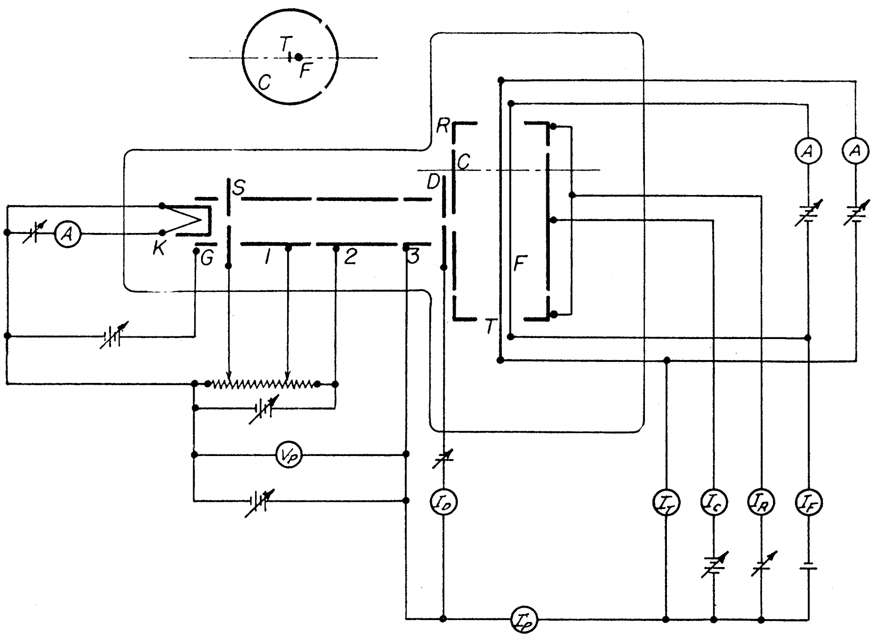

FIG. 1. Schematic diagram of experimental tube and circuit for secondary emission measurements.

changes in secondary emission coefficient result solely from changes in work function when monomolecular impurity films are deposited on a target surface. Other recent work[3] has expressed lack of agreement with this theory, and indicates that at least in the case of metals there is no correlation between change in work function and change in secondary emission coefficient. It is not impossible that some of the apparent disagreement has come about as a result of the technical difficulties encountered in obtaining an initially clean surface, and in clearly defining subsequent conditions brought about by contaminants; therefore, the present work was undertaken in an effort to remove some of the disagreement and possibly to gain a fuller knowledge of the fundamental physics of the secondary emission process.

Measurements were taken of the total number of secondary electrons produced when a well-focused beam of primary electrons was allowed to strike a carefully prepared tungsten target. A one-mm diameter beam cross section was always maintained at the target, and the range over which the primary voltage was varied extended from 100 to 1000 volts. The maximum in the secondary emission characteristic lies in this region. Targets used were in the form of a tungsten ribbon four cm long, 0.2 cm wide and one mil thick. These were initially flashed at 2700°K, which heat treatment produced a polycrystalline tungsten surface and dissuaded further crystal growth on additional heating. The crystalloids formed had faces exposed to the primary beam which were found to be on the average 100 square microns in area, so that about 1000 crystal faces were bombarded by the beam.

Preliminary observations on both clean and thorium-coated tungsten indicated the secondary emission coefficient to be independent of the primary current and target temperature. Measurements were taken for primary voltages of 200, 500 and 1000 volts, respectively, as the primary current was varied from 0.05 to 1.0 microampere, but changes in the secondary emission coefficient greater than one percent did not appear. This procedure was carried out for target temperatures from room temperature to about 1200°K where thermionic emission could be detected, but no changes in secondary emission were observed.

METHOD AND APPARATUS

The tube and circuit employed are quite similar to those already described.[3, 4] Fig. 1 is a schematic diagram of the experimental arrangement. The tube design includes the particular features: (1) the *electron gun* has the electrode system (G, S, 1) for concentrating the space charge in the cathode region into the primary beam, and a final retarding potential lens (2, 3) for keeping secondaries produced within the gun out of the primary current. This arrangement allowed wide and independent variations of both primary voltage and beam current density without causing an appreciable spread in electron energies. (2) The *collector system* (C, R) consists of three tantalum cylinders, 1.5 inches in diameter and mounted coaxially with the target along the axis. For thermionic emission measurements the arrangement was connected in the usual fashion with anode (C) and two guard rings (R). The ratio of the cylinder diameter to the target cross-sectional dimensions was made large so that the field a short distance from the target was approximately radial. For secondary emission measurements the anode and guard rings were connected together so as to form a collector almost completely surrounding the target. The primary current was taken as the current I_p entering the collector system when the beam was focused to clear the stop (D). The back quarter of the main collector (C) could be insulated from the rest of the system, and a thin willemite screen sprayed on the inside of this collector was useful in focusing the beam and in observing its cross section. The actual current to this quarter section when the beam was focused on the target supplied additional information concerning the aberrations suffered by the primary beam. For both thermionic and secondary currents the collector system was maintained at 40 volts positive with respect to the target, which potential was sufficient to draw saturation current in both cases.

All experimental tubes were sealed off from the vacuum system before measurements were taken. The only materials besides glass used in construction were tungsten, monel metal, outgassed tantalum, and to a very small extent, outgassed nickel. The technique used in the preparation of structural parts for vacuum and the schedule of evacuation have been described by Nottingham.[5]

The procedure for obtaining a clean surface of pure tungsten was necessarily empirical. The surface was assumed to be in the state desired when the results obtained were reproducible

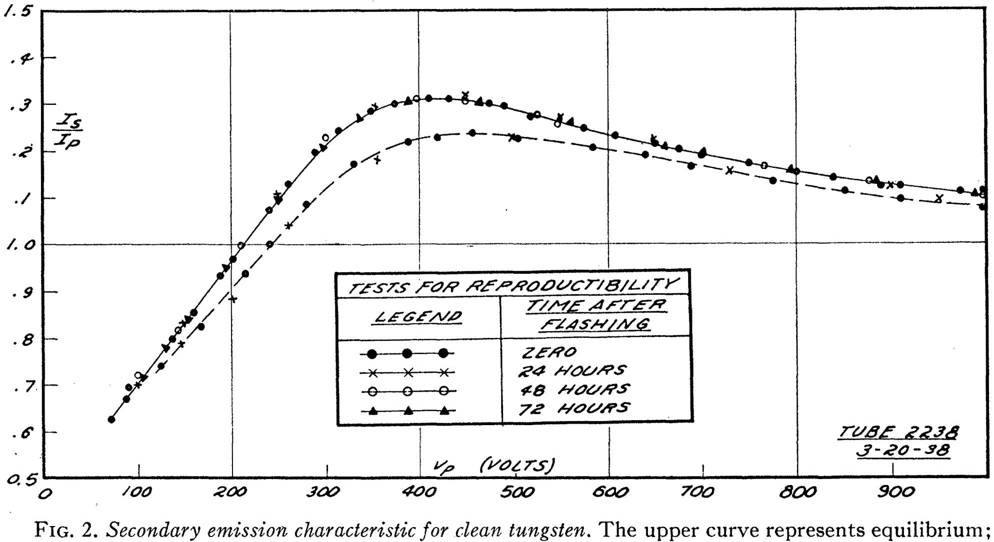

FIG. 2. *Secondary emission characteristic for clean tungsten.* The upper curve represents equilibrium; in this state tungsten could be evaporated from the target at 2800°K without changing the yield of secondary electrons. Dashed line, after flashing at 2700°K and heating at 1800°K for 10 hours. Solid line, equilibrium after successively flashing at 2700°K and heating at 1800°K over a period of 120 hours.

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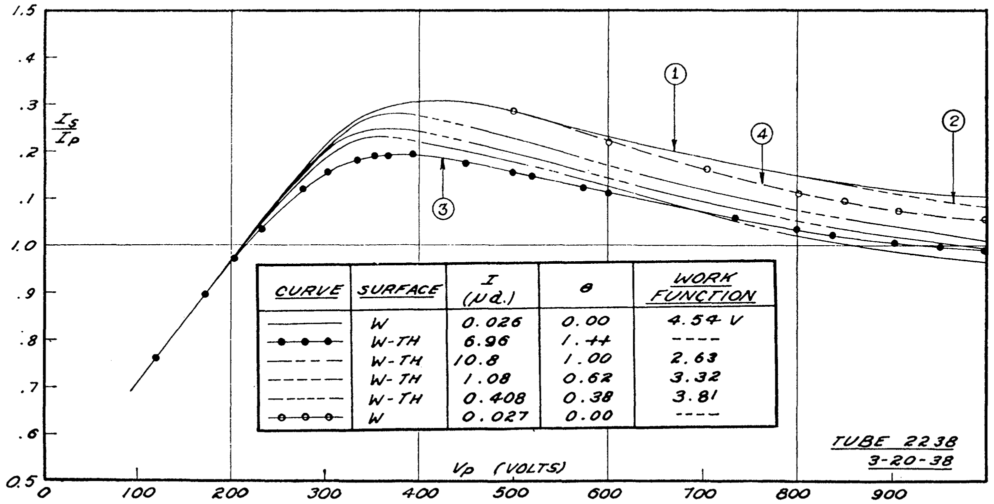
[4] H. E. Farnsworth, Phys. Rev. **25**, 41 (1925).

[5] W. B. Nottingham, J. App. Phys. **8**, 762 (1937).



CURVE	SURFACE	I (μa.)	θ	WORK FUNCTION
———	W	0.026	0.00	4.54 V
—●—●—●—	W-TH	6.96	1.44	----
—— — — —	W-TH	10.8	1.00	2.63
— — — — —	W-TH	1.08	0.62	3.32
— - - - - —	W-TH	0.408	0.38	3.81
—○—○—○—	W	0.027	0.00	----

FIG. 3. *Secondary emission characteristic for thorium-coated tungsten.* The primary current was of the order of 1 microampere, at all values of primary voltage. I = emission current at 1200°K. $\theta = (\log I_\theta - \log I_w)/(\log I_T - \log I_w)$.

within one percent regardless of subsequent treatment given the target. This condition was demanded for both thermionic and secondary currents. The procedure finally adopted consisted in successive short period flashings of the target at 2700°K followed by a long period of heating at 1800°K. The final results of this procedure are shown in Fig. 2. The short high temperature heating usually caused a rise in the secondary emission characteristic over that illustrated by the equilibrium curve. The long heating at 1800°K brought the characteristic down gradually to the values represented by the lower curve. After repeating this process a number of times the state of equilibrium was reached after which further heat treatment had no effect; in this state tungsten was evaporated from the target at 2800°K without changing the surface properties. One is led to suspect that the phenomena involved here are similar to those accompanying flashing and activation of thoriated tungsten. The high temperature flash decomposes metallic impurities in the target; the lower temperature heating causes the diffusion of occluded gases and low melting-point metals to the surface, where the gases evaporate and are pumped away and the metals form a monatomic film on the target. This state is represented by the lower curve of Fig. 2. When the target has been freed of body impurities in this manner the final flash cleans adsorbed substances from the surface. That such a process does occur was confirmed by observing patterns from the target undergoing heat treatment in an electron projection tube.[6] The upper curve of Fig. 2. is offered as an accurate secondary emission characteristic for polycrystalline tungsten. It has its maximum at 420 volts where the secondary emission coefficient reaches a value of 1.31.

Experiments on thoriated tungsten filaments led finally to their adoption as a thorium source, after it was found a practical impossibility to outgas bulk thorium. The filament (*F*) was a one-mm thoriated tungsten spiral mounted two mm behind the target out of sight of the gun. The schedule adopted for the deposition of thorium on the target was based on the following fairly well established set of observed facts: (1) After flashing a Th-W filament at 3000°K, and then reducing the temperature to 2500°K, quite gas-free thorium comes off. (2) Gas, presumably oxygen, comes off quite freely at about 1800°K. (3) A clean tungsten filament, or a tungsten filament covered with thorium when held at 1600°K will not take up a gas evolved from the thoriated tungsten source.

In view of this experimental work the follow-

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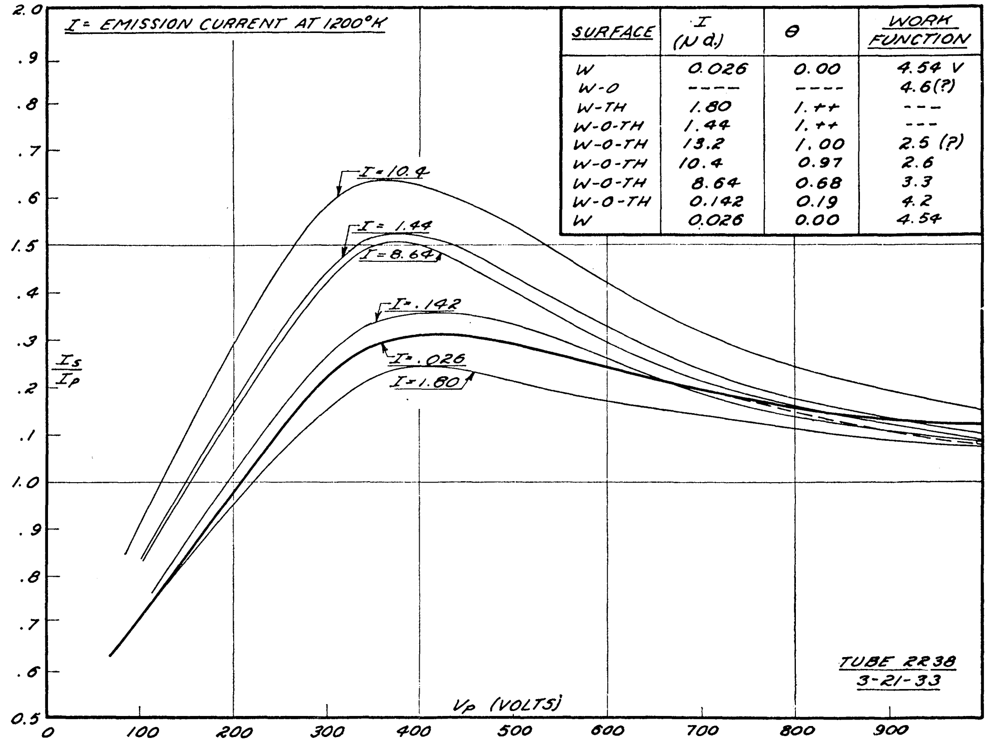
[6] The tube was a simple electron microscope such as described by R. P. Johnson, J. App. Phys. 9, 508 (1938).



SURFACE	I (μ a.)	θ	WORK FUNCTION
W	0.026	0.00	4.54 V
W-O	----	----	4.6(?)
W-TH	1.80	1.++	---
W-O-TH	1.44	1.++	---
W-O-TH	13.2	1.00	2.5 (?)
W-O-TH	10.4	0.97	2.6
W-O-TH	8.64	0.68	3.3
W-O-TH	0.142	0.19	4.2
W	0.026	0.00	4.54

FIG. 4. *Secondary emission characteristic for oxygenated thorium-coated tungsten.*

ing procedure was followed for evaporating thorium in the secondary emission tubes: (*a*) the target *T*, after heat treatment, was set at 1600°K; (*b*) the Th-W filament F was flashed and then held at 2500°K for evaporation of throium, at which time the target was brought down to about 1000°K; (*c*) after the evaporation period the target was brought up to 1600°K and the Th-W filament reduced to room temperature; (*d*) thermionic current was read from the target at 1200°K to check the condition of the surface, which was not altered at this temperature.

EXPERIMENTAL RESULTS

Figure 3 is a set of secondary emission characteristics for clean thorium on clean tungsten. To represent the degree of thoriation the parameter θ, which is simply related to the work function ϕ, was chosen.[7]

$$\theta=\frac{\log I_\theta-\log I_w}{\log I_T-\log I_w}=\frac{\phi_\theta-\phi_w}{\phi_T-\phi_w},$$

where I_θ = thermionic emission at any state, for which the work function is ϕ_θ; I_w = thermionic emission for clean tungsten, for which the work function is ϕ_w; and I_T = maximum thermionic emission for which the work function is ϕ_T. The table of Fig. 3 gives the values of θ and ϕ for the corresponding graphical representation of the results. The set of (Th-W) curves are for the second cycle of thoriation. Note that the curve for clean tungsten at the beginning of the cycle does not reproduce in the high voltage range when all the thorium is evaporated from the target surface. Curve (1) represents the secondary emission characteristic for clean tungsten reproduced from Fig. 2. Thorium was deposited until θ became greater than unity. When the thorium was evaporated off, curve (2) represents the final state, and this did not change even when the target was raised to 2800°K at which temperature tungsten evap-

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[7] S. Dushman, Rev. Mod. Phys. **2**, 381 (1930). It should be understood that θ is not intended to represent the fraction of the tungsten surface covered with thorium; for $\theta = 1$ the true coverage is probably about 0.75.

orated freely. Again thorium was deposited onto the target until θ became greater than unity, at which time curve (3) was obtained. The dashed curves represent the intervening stages gone through in the step evaporation back to the equilibrium value represented by curve (4). Here tungsten was again evaporated from the surface at 2800°K without an apparent change in surface conditions. It appears that at temperatures at which thorium evaporates from the surface it also diffuses into the metallic lattice, and probably forms a solid solution of thorium in tungsten which might be considered a constant boiling solution.

Figure 4 gives the results for oxygenated thorium-on-tungsten. Starting with clean tungsten given by the curve ($I=0.026$) thorium was deposited until θ became greater than unity; this gave the secondary emission characteristic ($I=1.80$). Then with the target cold, the filament F was heated for a few minutes at about 1800°K to release oxygen. The secondary emission coefficient changed according to the curve ($I=1.44$), which indicates a small increase in work function and a greatly increased secondary emission coefficient. When thorium was then evaporated from the surface the secondary emission became greater as the work function decreased (table of Fig. 4), and the ability to evaporate the thorium without causing any apparent change in structure except the lowering of work function suggests that the oxygen might be adsorbed to the tungsten under the thorium. For computing the values of the table in Fig. 4 the work function for the ($W-O$) surface was assumed to reach a value of 4.6 volts, and for monomolecular layer of thorium-on-oxygen-on-tungsten corresponding to $\theta=1$, the work function was taken as 2.5 volts. These values were chosen to give a range of variation of contact potential approximately the same as observed by Treloar[2] in his experiments on thoriated tungsten.

Interpretation of Data

A theory of secondary emission based on the quantum mechanics of metals as initiated by Bloch has been given by Fröhlich.[8] Theories based on the same picture have been given for the related phenomena of thermionic emission and surface photoelectric effect,[9] but all of these treatments have considered only simplified models of the metal surface. The action of the surface has usually been represented by simple smooth or step-potential curves, while in reality even for a pure metal the situation is much more complicated. It would be difficult to give the right model for a more accurate theory of secondary emission; however, one might hope for some progress in the direction of a more improved picture of the surface for the process from considerations of the related electronic phenomena which depend strongly on surface conditions: (*a*) In *thermionic emission* simple theory leads to an equation for the emission current density:

$$I=ADT^2e^{-\phi e/kT}.$$

While problems of transmission and reflection in the surface field are not understood completely enough to give the precise value of the transmission coefficient D in any individual case, values of the work function ϕ (at least for the case of tungsten) are reproducible, and the variations in emission with work function caused by adding monomolecular films of foreign substances may be fairly well predicted.[10] (*b*) In the case of the *surface photoelectric effect* difficulties are likewise experienced in giving an explanation of transmission coefficients for the real case,[11] but the dependence of current on work function seems to check simple theory.

In the case of *secondary emission* if one does not consider absorption, simple theory shows that at least up to the maximum of the secondary emission curve the current should depend very little on the height of the potential barrier, and hence one could look for little dependence on work function. The results plotted in Fig. 3 certainly do not show any systematic variation when the work function of tungsten is changed by thoriation. Experiment (see Fig. 3) has the secondary emission coefficient decreasing for greater amounts of thorium on the surface, and the

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[8] H. Fröhlich, Ann. d. Physik **13**, 229 (1932).

[9] See F. Seitz and R. Johnson, J. App. Phys. **8**, 246 (1937).

[10] See A. L. Reimann, *Thermionic Emission* (John Wiley & Sons, 1934), Chapter III.

[11] A. G. Hill, Phys. Rev. **53**, 184 (1938).

condition $\theta = 1$ has no unique significance. Below 200 volts the secondary emission coefficient appears to be independent of the amount of thorium on the surface and is the same as for clean tungsten. One could speculate that this case might correspond to a simple metal, the collision cross section being independent of thoriation, so that the emission process is independent of the nature of the surface barrier. This would be in agreement with the approximate theory of Fröhlich, but it is more probable that a number of conflicting processes average to give the result.

For the range of voltages including the maximum of the curves in Fig. 3 it is significant that the maximum shifts to lower voltages for coverage with thorium. Assuming that the excitation process does not change on thoriation an interesting calculation comes out of classical theory. The dependence of the primary voltage for maximum secondary emission coefficient on the density of the metal has been computed classically.[12] The result is that the primary energy for maximum secondary emission coefficient should vary as the square root of the density of the metal.

Density of tungsten $= 18.7$ grams/cm^3
Density of thorium $= 11.2$ grams/cm^3
$V_W =$ primary voltage for maximum I_s/I_p for tungsten $= 420$ volts for Fig. 2
$V_T =$ primary voltage for maximum I_s/I_p for thorium $= 420\ (11.2/18.7)^{\frac{1}{2}} = 326$ volts.

This value compared with the maximum of 350 volts from curve (4) of Fig 3 is in fair agreement, considering that the target consisted of thorium on tungsten rather than pure thorium. One might go farther with the classical picture and attribute the fewer secondary electrons obtained in the case of thorium-coated tungsten to the liberation of secondaries farther below the surface than in the case of clean tungsten, and hence, the lower probability of escape. It is not improbable that the classical picture fits the experimental data fairly well because it is consistent with the damping of electron waves in crystals as developed by Slater.[13]

A reasonable explanation can be assigned to the variation of secondary emission coefficient with change in work function for the case of oxygenated thorium-coated tungsten expressed in Fig. 4. In the energy band picture this structure would correspond roughly to a semiconducting surface. The Fermi levels for this case would be separated from the first energy band by a forbidden region, and since the lower zone would be completely filled and the upper zone completely empty, transitions would be allowed to the upper region. Besides, if one should view the structure very near the surface probably many impurity states exist, and a large collision cross section would be presented to the incoming primary electrons. The excitation and emission processes in this case could be quite analogous to the surface photoelectric effect, and the secondary emission coefficient would be expected to vary with the work function in the manner that has been predicted.[2]

While it is thus possible to find reasonable explanations for experimental results on the secondary emission from composite surfaces much more data must be taken under controlled conditions before an accurate description of the physical processes can be formed.

I am deeply grateful to the many people who have given me assistance in this work. I wish to thank particularly Professor W. B. Nottingham for his many suggestions; Dr. L. B. Headrick of the RCA Manufacturing Company for his material assistance and advice in the matter of electron gun design; and Dr. R. B. Nelson for his suggestions on the treatment of targets. My thanks are due, also, to Mr. Walter Ennis for his assistance in the glass-working operations demanded in this problem.

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[12] D. R. Bhawalkur, Proc. Indian Acad. Sci. **6**, 74 (1937).

[13] J. C. Slater, Phys. Rev. **51**, 840 (1937).