closer resemblance, the curves being very similar in shape and sign to those for ΔE except in the case of nickel where Δl is negative and ΔE positive. In the case of iron the analogy is very close, the Δl *vs.* H curves showing the type of maxima in Fig. 2. In the case of the change of length an explanation has been found by studying single crystals. For iron the (100) is the direction of easiest and the (111) of hardest magnetization, and Δl is always positive for the former and negative for the latter.[20] A polycrystalline specimen would therefore show the combined effects for single crystals magnetized parallel to (100) and (111) directions, respectively, the direction of easy magnetization predominating for low fields. The same explanation may be advanced for the ΔE curves. The following summarizes the picture: According to Weiss' and later theories a ferromagnetic substance is regarded as containing regions or "blocks" of the order of 10^5 atoms which are magnetized to saturation without an external field; on gradually increasing the external field the "blocks" are lined up parallel to that (100) direction in each crystal nearest that of H, thereby increasing l and E, the resistance, R, remaining unchanged; finally in strong fields the "blocks" must turn slowly from (100) directions into more exact parallelism with H or somewhat in (111) directions, thereby decreasing l and E and increasing R. A similar picture follows for the other metals. In the case of nickel Δl is of the same sign[21] and hence also ΔE for all directions and the (111) is the direction of easiest magnetization. It would appear that ΔE and Δl are both due to the same thing.

The above conclusions are in accord with those of Akulov[22] and Chramov and Lwowa,[23] who conclude that ΔE may be produced by magnetization or stretching and is conditioned by (1) crystal structure of specimen, (2) change of direction of resulting spins in separate crystal regions.

[20] W. L. Webster, Proc. Roy. Soc. **A109**, 570 (1925); Proc. Phys. Soc. **42**, 431 (1930).

[21] Mashiyama, Sci. Rep. Tohôku Univ. **17**, 948 (1928).
[22] N. Akulov, Zeits. f. Physik **87**, 768 (1934).
[23] P. Chramov and L. Lwowa, Zeits. f. Physik **89**, 443 (1934).

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The Relation Between the Electron Field Emission and the Work Function of Liquid Mercury

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The variation in the field necessary to initiate a vacuum discharge between a mercury cathode and a molybdenum anode and the accompanying variation in the work function of the cathode have been measured. The work function variations were obtained from measurements of the contact potential between the mercury and a platinum filament. The fields were applied by an impulse circuit, the time constant of the voltage wave being very short in order to prevent distortion of the mercury. The final results show a variation of the field with work function which, while in the same direction, is more pronounced than that forecast by the Fowler-Nordheim theory. For a change of work function of one volt the field required to initiate the discharge varied from 375 kv/cm to 575 kv/cm.

INTRODUCTION

NUMEROUS experiments[1] have been performed to study the relation between the field current and the field strengths involved. Several theories[2] have been proposed to forecast what this relation should be or to fit the experimentally found relation, the latest being that of Fowler and Nordheim. As a whole the results of various experiments on the problem have been capable, after making an assumption regarding the work function of the surface serving as cathode, of being fitted to an expression such as they have deduced.[3] The present experiments were carried out to investigate the relation con-

[1] Millikan and Eyring, Phys. Rev. **27**, 51 (1926); Eyring, Mackeown and Millikan, Phys. Rev. **31**, 900 (1928); Gossling, Phil. Mag. **1**, 609 (1926); Millikan and Lauritsen, Proc. Nat. Acad. Sci. **14**, 46 (1928).
[2] Schottky, Zeits. f. Physik **14**, 63 (1923); Richardson, Proc. Roy. Soc. **A117**, 173 (1928); Houston, Zeits. f. Physik **47**, 33 (1928); Fowler and Nordheim, Proc. Roy. Soc. **A119**, 173 (1928).

[3] Stern, Gossling and Fowler, Proc. Roy. Soc. **A124**, 699 (1929).

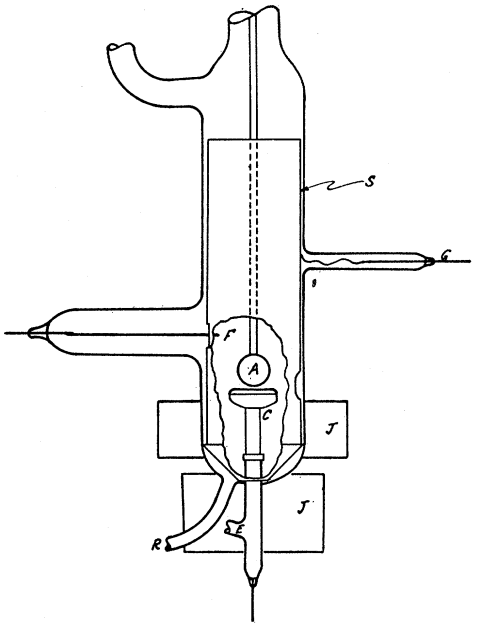

FIG. 1. The discharge tube.

necting the work function and the field with a fixed current density.

It has been shown[4] that a vacuum spark is initiated by field emission from the cathode. The rapid variation of the current density with field justifies the assumption that the density to start the discharge is practically constant, or if not constant, at least the variation of field will be small over the range of variation of the required current, on the assumption the criterion used for the field emission was the passage of a discharge between the cathode being studied and the anode. This does away with the need of measuring the current and thereby simplifies the use of impulsive fields which have a decided advantage in the experiment as described below.

Mercury was chosen as the cathode material both on account of the ease with which its work function could be varied by vacuum distillation and because it would automatically assume a plane surface, free of polish imperfections. However, this eliminated the possibility of using steady fields, since a steady field would very seriously distort the surface and thus make impossible a fair calculation of the field strength from the value of the applied voltage. This called for impulsive potentials of short duration to avoid any appreciable movement of the mercury.

The method adopted for measuring the work function was to measure the contact potential between the mercury and some fixed standard. It has been shown by several investigators[5] that the contact potential difference between two metals is equal to the difference of their work functions except for a negligible correction. Cassel and Glückauf[6] have shown that mercury vapor has no effect on the work function of a platinum filament, so platinum was chosen as the standard for measuring the contact potential.

APPARATUS

The discharge tube is shown in Fig. 1. In addition to the part shown here, there was an extension of the upper part with an enclosed armature by means of which the spherical anode could be drawn into the upper part of the tube. The Pyrex glass envelope, 6.5×25 cm, was lined with a nickel shield to reduce disturbing effects in the electrometer circuit used for measuring the contact potential. The platinum filament F, 0.2 mm diameter and 2.5 cm long, was inserted from the side, supported by leads of 100 mil nickel wire. The cathode consisted of the mercury contained in the iron cup C, 3.5 cm diameter and about 1.2 cm deep, and which was sealed to the glass with silver chloride. Iron was chosen to eliminate the accumulation of electric charges by the overflowing mercury. The condition of the mercury surface could be altered by distillation similar to the method described by Beams.[4] The mercury entered from the still at E, flowed up to the cup, overflowed and returned to the still through the tube R. A two cm molybdenum sphere A was suspended above the mercury to form the anode for the field emission measurements. The support for this was the iron rod shown extending into the upper part of the tube. The sections J were jackets for packing dry ice to lower the vapor pressure of the mercury.

[4] Snoddy, Phys. Rev. **37**, 1678 (1931); Beams, Phys. Rev. **44**, 803 (1933).

[5] Richardson, Phil. Mag. **23**, 261, 615 (1912); see also Darrow, Phys. Rev. Supp. **1**, 147 (1929); Richardson and Compton, Phil. Mag. **24**, 575 (1912); Millikan, Phys. Rev. **18**, 236 (1921); Richardson and Robertson, Phil. Mag. **43**, 557 (1922); Van Voorhis, Phys. Rev. **30**, 318 (1928).

[6] Cassel and Glückauf, Zeits. f. physik. Chemie **18**, 347 (1932).

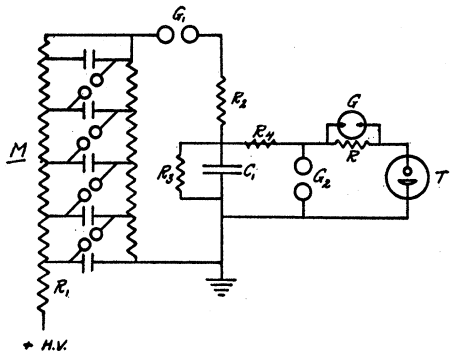

FIG. 2. Method of applying impulse potential.

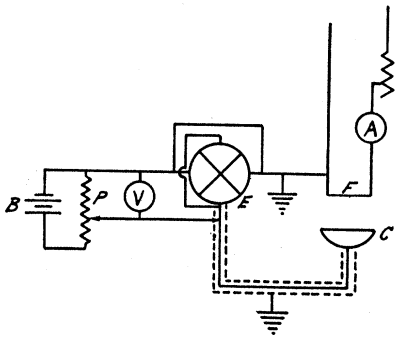

FIG. 3. Circuit for measuring contact potential between the mercury and platinum.

The vacuum system was standard with liquid air trap, McLeod gauge, two-stage mercury pump with the oil fore pump. However, no stopcocks were used except at the fore pump, all other cutoffs being of the mercury type. There was one, which was kept closed except when the pumps were operating, between the diffusion pump and the stopcock in order to decrease the danger of grease vapors getting into the system. The entire system except for the fore pump was mounted on a heavy table which was set on automobile inner tubes to eliminate transmission of building vibrations to the mercury surface serving as cathode.

Fig. 2 shows the high voltage impulse circuit. This circuit was charged by an x-ray transformer and synchronous rectifier system adjusted to supply about 28 kv to ground. The impulse circuit itself consists of the Marx circuit M, the isolating gap G_1 (12.5 cm brass hemispheres) charging resistor R_2 and condenser C_1, measuring gap G_2 (10 cm brass spheres), resistor R and glow tube G, and the discharge tube T. The glow tube was used to indicate the presence of oscillations and to show the polarity of the discharge. The resistors in the various circuits were adjusted to values to prevent oscillations. The Marx circuit was set to deliver about 85 kv peak. G_2 was irradiated with ultraviolet light from an iron arc during all measurements.

The electrical connections used in determining the contact potential difference of the filament and mercury are shown in Fig. 3. Here F is the filament and G the cup of mercury of the discharge tube. E is a Swann electrometer which was operated heterostatically. The lead from the tube to the electrometer insulated quadrants consisted of a wire surrounded by 2.5 cm brass tubing, the wires being insulated by sealing wax in the ends of the tube. The quadrants and mercury system were charged from the B battery and potentiometer arrangement P. All connections in the electrometer system were soldered to prevent changes of their contact potentials.

Before any measurements were taken the tube and mercury still were baked about 5 hours at 300–350°C, the rest of the vacuum system being torched out in the meantime. The first part of this baking was done with no liquid air on the trap and the latter part with it. Liquid air was then kept on the trap continuously until all measurements were completed. After baking out the system the mercury, which had been cleaned by the Roller[7] process, was put in and the system immediately re-evacuated. All parts of the system which enclosed moving mercury had to be painted with "Aquadag" on the outside and wrapped in tin foil to prevent disturbing charges as much as possible.

Before making any tests the platinum filament of the tube was heated for several minutes at a current higher than that needed for the tests, and heating continued for a half-hour at the test current. Before each measurement the filament was again heated for a few minutes to drive off any mercury which might have condensed on it.

PROCEDURE

The sphere A of Fig. 1 was drawn up to the upper part of the tube and held there while

[7] Roller, J. O. S. A. and R. S. I. **18**, 357 (1929).

making contact potential measurements. The sphere and shield of the tube were grounded and the filament energized at constant current. For the contact potential determinations the electrometer quadrant and mercury system were charged to a definite voltage with respect to ground. Then this system was isolated by raising the key of the electrometer for five seconds. The deflection of the electrometer needle for this period gave a measure of the current which had passed between the filament and the mercury. Several values of the voltage applied to the mercury then gave enough points to plot a curve of the thermionic characteristic of the diode formed by the filament and the mercury. Displacements of these characteristics along the voltage axis between different runs gave the change of contact potential difference between the tube elements, and since the platinum does not change its surface condition this gives the change in the mercury surface. Another method of determining this change of contact potential was to charge the electrometer to a given potential as before and then raise the key and let the system discharge to equilibrium. This point gave the value of the voltage when the potential still applied to the mercury was equal and opposite to the contact potential difference of the mercury and platinum, thus the net voltage across the tube was zero and there was no passage of electrons from the filament to the mercury. These two methods checked almost exactly. These changes in contact potential difference are equal to changes in work function of the mercury.

The surface condition having been determined, the sphere was lowered into position just above the mercury surface and the field necessary to initiate a vacuum discharge was taken. The Marx circuit, Fig. 2, was energized and the measuring gap G_2 set to a small value. When the impulse circuit fired, the condenser C_1 charged, at a rate determined by R_2, until the voltage across G_2 was sufficient for breakdown, when it removed the potential from the tube. The next impulse was applied with G_2 set a little wider and so on until a value of G_2 spacing was reached when the discharge went through the tube instead of to the measuring gap. This value of the gap spacing then gave the value of the voltage necessary to initiate the discharge between the sphere and the

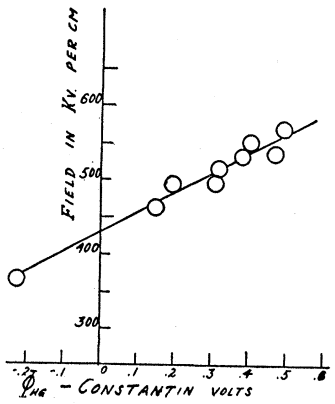

FIG. 4. Breakdown field as a function of the work function of the mercury.

mercury. The actual field at the surface could then be calculated from the expression[8]

$$E=2V/(f+1)x,$$

where E is the field, V the impressed voltage, f a function of x and the radius of the sphere, is found from tables, while x is the spacing between the sphere and the mercury. This latter quantity was determined by means of a telescope with movable cross-hairs.

Having obtained a complete set of data in this way, the mercury surface was altered. This was done in several ways and the result was uncontrollable. Sometimes the mercury was distilled, a new set of data being taken just after it overflowed in the cup. At others it was allowed to stand for long periods without distilling. These usually changed the surface condition but a given treatment did not always give the same sort of change. This, however, was unimportant since the surface condition was actually measured and a change of some sort was all that was wanted. After changing the surface new data were taken for the surface and the field, giving another point on the curve.

RESULTS

The curve of Fig. 4 summarizes the results. The fields necessary to initiate the vacuum discharge are plotted as ordinates and the changes in work function as abscissae. These values give the straight line within the precision of the data

[8] Peek, *Dielectric Phenomena* (Van Nostrand, 1929).

which is about 3 percent. Before considering the comparison with the theory, let us consider the consistency of the data themselves. These points do not represent a progressive change from day to day, as the uncontrollable changes of the mercury surface made the location of the points a random process with time. No adjacent points represent data taken on consecutive runs. This rules out any change of a progressive drift due to something else. The manner in which these randomly determined points all fall on the same curve is strong support for the reliability of the results.

When these results are compared with those forecast by the theory of Fowler and Nordheim, we note two differences. The first of these is the marked difference in the order of the fields, those forecast being of the order of 10^7 volts/cm. This is in agreement with the results of Beams.[4] A possible explanation of this might be a distortion of the mercury either by the field or by mechanical disturbances. The first was prevented by the short time of application of the voltage pulse (10^{-7} sec. time constant) and was checked by applying pulses of different wave fronts. Since any distortion by the field would grow with increased time of application of the voltage, this time was varied and the breakdown measured. For a variation of the time from 10^{-7} to 10^{-6} sec. there was no observable change in the field necessary for breakdown. A second check was made by putting ripples on the surface of the mercury. A coil containing a loose iron core was placed on the table with the vacuum system and connected to the 60-cycle supply, thus giving the mercury a 120-cycle agitation. The effect of this was to decrease the field needed by about 6 percent for the wave front used in the experiment and somewhat more for the slower waves. The effect under the conditions of the experiment is very close to that calculated for the intensification of the field by the ripple. This would not have been true if irregularities had been present.

The second difference with the theory is in the difference in the influence of the work function. The effect found here for this quantity, while in the same direction, is more than forecast by the Fowler-Nordheim equation. The equation gives a 30 percent change of field for 1 volt variation of work function while the experiment gives about 60 percent change.

We are thus led to the conclusion that, while the work function has a marked effect on the field emission, the theory fails quantitatively to fit the experimental results. To simplify the mathematics a sharp potential barrier at the surface of the metal was assumed—that is, the barrier was represented as a rectangular step, the effect of the external field being assumed to change this to a sort of triangular barrier, the edge of the metal still being represented by a vertical rise. This picture is no doubt too simplified, the actual barrier probably being some sort of irregular affair before the application of the field, and the effect of the applied field penetrating slightly into the metal. Both of these would have the result of increasing the effect of any work function variation on the field emission as was observed.

Acknowledgments

In conclusion I wish to express my appreciation to Dr. J. W. Beams for guidance and encouragement in the course of the work, and to Dr. C. M. Sparrow for discussions of the results and for aid in computing the effect of the ripples on the mercury. I am also indebted to Mr. D. D. Knowles of the Westinghouse Research Laboratories for the loan of apparatus.