light, that in c^{-1} being absent. But such procedure is, strictly speaking, not permissible. In classical electrodynamics, the retarded potentials which one encounters are solutions of Maxwell's equations; they appear as necessary generalizations of Coulomb's law. In nuclear physics, where the potential functions used hitherto are entirely arbitrary, the use of retarded functions has no meaning whatever.

2. Even if, following the classical analogy, retarded potentials are introduced, no exact calculation can be made. For there will then appear damping terms corresponding to the classical radiation reaction, permitting no stationary solution. The first of these terms is of the order c^{-3}. To avoid them, the sequence must therefore be broken off after the term in c^{-2}. But in that case, the approximation would hardly be satisfactory and the calculation of doubtful utility.

AUGUST 15, 1936 PHYSICAL REVIEW VOLUME 50

The Relation Between Electron Field Emission and Contact Electromotive Force for Liquid Mercury

DAN H. MOORE, *University of Virginia*

(Received June 13, 1936)

The relation between contact e.m.f. and the impulsive potential necessary to initiate a vacuum spark has been studied for a liquid mercury cathode. The magnitude and time of application of the impulsive potential were determined by a cathode-ray oscillograph so that possible distortion of the mercury surface produced by the electric field could be evaluated. For impure mercury no definite relation could be found. However, for carefully distilled mercury the relation between the work function and breakdown field was in qualitative but not in quantitative agreement with theory.

THE impulsive potential necessary to produce a vacuum spark has been studied by Beams[1] and Quarles.[2] Beams has investigated the field emission from a liquid mercury cathode using impulsive potentials of approximately 10^{-6} sec. duration and, by means of a rotating mirror, has shown that the luminosity appears at the anode before the cathode which suggested that the breakdown was initiated by field emission from the cathode. Quarles has measured the breakdown fields between a mercury cathode and a molybdenum anode along with the accompanying variation in the work function of the mercury. His results, although qualitative, were not in quantitative agreement with the theoretical predictions of Fowler and Nordheim.[3]

The present investigation was undertaken to extend the work of Quarles over a wider range and to find, if possible, the effect of impurities on the relation between field emission and the work function. Also the applied impulses were investigated with a high speed cathode-ray oscillograph in order that the effect of possible distortion of the mercury surface on the field measurements, as suggested by Tonks,[4] could be evaluated.

OUTLINE OF PROCEDURE

The method consisted in measuring both the contact potential difference between a hot platinum filament and the mercury surface also the potential necessary to cause a vacuum spark between the mercury and a molybdenum sphere. The contact potential is a measure of the difference between the work functions of the two surfaces.[5, 6] The work function of platinum is assumed constant. Moreover, Cassel and Glückauf[7] have found that mercury vapor does not affect the work function of platinum. There-

[1] Beams, Phys. Rev. **44**, 803 (1933).
[2] Quarles, Phys. Rev. **48**, 260 (1935).
[3] Fowler and Nordheim, Proc. Roy. Soc. **A119**, 173 (1928).
[4] Tonks, Phys. Rev. **48**, 562 (1935).
[5] Mönch, Zeits. f. Physik **65**, 233 (1930).
[6] Eckart, Zeits. f. Physik **47**, 38 (1929).
[7] Cassel and Glückauf, Zeits. f. physik. Chemie 18 Abt. B 4–5, 347 (1932).

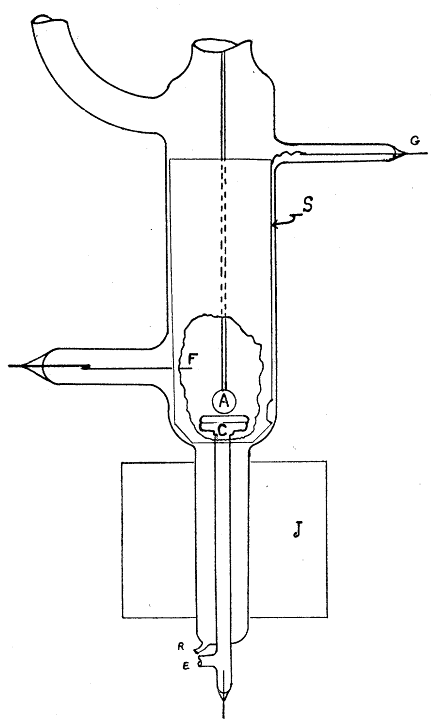

FIG. 1. Discharge tube.

fore, if the filament is kept at a fixed temperature, the change in contact potential gives the change in work function of the mercury.[8]

APPARATUS

The tube in which the measurements were made is shown in Fig. 1. It was sealed to a standard vacuum system. In order to minimize grease vapors, no stopcocks were used, all cut-offs being of the mercury type. The tube consisted of two parts—a main part about 20 cm long and 6.5 cm in diameter which was lined with a grounded nickel shield S, except for two openings, one for the filament leads and the other for observing the gap; a bottom part about 15 cm long and 3.8 cm in diameter, which permitted the removal of the mercury system without disturbing the rest of the tube, also gave space for packing dry ice in the jacket J to reduce mercury vapor pressure. An upper part, not shown, contained an aluminum support for the iron rod which held the sphere in place. Above this there was space for the rod and sphere to be lifted by an electromagnet out of the way while making measurements on contact potentials. The platinum filament F, 0.2 mm in diameter and 2.5 cm long was inserted from the side and welded to 100 mil nickel wire supports. The cathode consisted of the mercury contained in an iron cup C. The cup was 3.5 cm in diameter and the bottom fitted tightly into a 12 mm glass tube which conveyed the mercury from the condenser of a still. The mercury after overflowing the cup, thus changing the cathode surface, returned to the still through the tube R. The iron served to prevent the overflowing mercury from setting up charges which would interfere with the electrometer readings. The molybdenum spherical anode A was 2 cm in diameter and, when in position for a breakdown, was from 0.7 to 1.5 mm above the mercury surface, this distance being carefully measured each time with a telescope with micrometer eyepiece. The tube was mounted on a

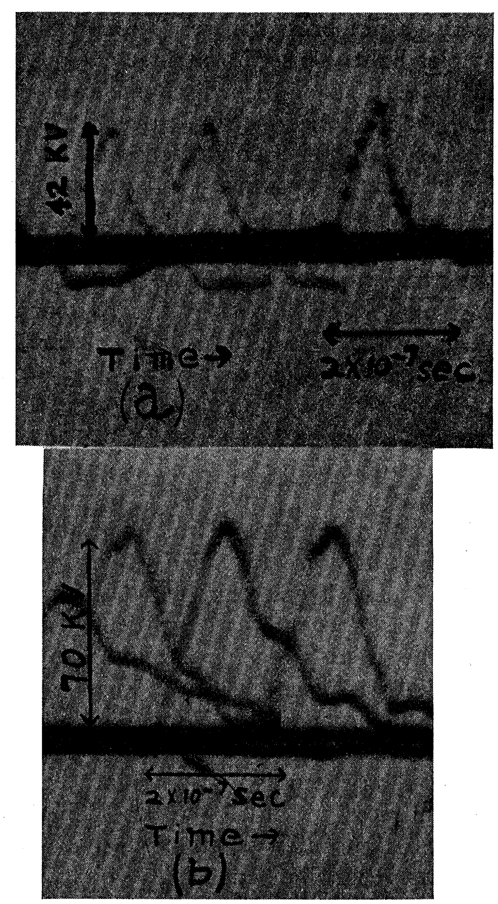

FIG. 2. Oscillograms of the impulse when the spark occurred (a) at the auxiliary gap, (b) at the vacuum gap.

[8] Compton and Langmuir, Rev. Mod. Phys. **2**, 145 (1930).

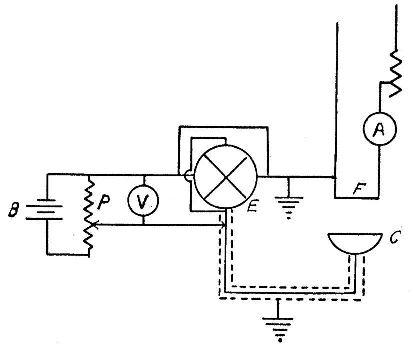

FIG. 3. Electrometer circuit for measuring contact potentials.

heavy table which floated on automobile inner tubes.

The impulses from the Marx circuit, set for 100 kv, were applied to the anode through the upper part of the tube. In parallel with the vacuum gap was a small condenser and an auxiliary gap of brass spheres illuminated with ultraviolet light. This gap, at first narrow, was gradually widened until a discharge took place in the vacuum tube, the final spacing giving a measure of the applied potential from which the field at the mercury surface was calculated. Fig. 2a gives oscillograms of the impulse when the breakdown occurred in the auxiliary gap. In this case the gap was set for 42 kv. Fig. 2b shows oscillograms of the breakdown in the mercury-molybdenum gap. The breakdown occurs at 70 kv, which is higher than the voltages used when the accompanying contact potential was measured. The potential rises in 1.1×10^{-7} sec.

The electrometer circuit used in making the contact potential measurements is shown in Fig. 3. The filament F and two quadrants of the electrometer, E, were grounded while the other two quadrants, the mercury cup C, and leads, connected as shown, were well shielded. All connections were soldered. After flashing the filament it was heated with a fixed current sufficient for thermionic emission. The quantity of charge that flowed from filament to mercury depended upon the potential difference between the two surfaces and upon the time. Therefore, for a given time interval, the deflection of the electrometer could be reduced to volts. A zero deflection would correspond to zero difference between contact and applied electromotive forces.

TABLE I. *Data on commercial mercury.*

Contact potential Pt−Hg (volts)	Field (volts per cm)	Contact potential Pt−Hg (volts)	Field (volts per cm)
−0.82	486,000	−0.88	520,000
−0.83	491,000	−1.20	530,000
−0.89	490,000	−0.79	725,000
−0.95	495,000	−1.40	730,000

TABLE II. *Data on purified mercury.*

Contact potential Pt−Hg (volts)	Field (volts per cm)	Contact potential Pt−Hg (volts)	Field (volts per cm)
−0.65	320,000	−0.76	650,000
−1.00	590,000	−0.79	435,000
−0.80	460,000	−0.92	445,000
−0.46	590,000	−0.82	475,000

RESULTS AND CONCLUSIONS

The results were summarized in Tables I and II and in the graph of Fig. 4. The data for Table I were taken on ordinary commercial mercury. With the exception of three values there is little variation in either contact potential or field strength necessary to produce discharge. The three varied values were obtained after the system had been either opened to air and again evacuated or after the mercury surface had been definitely changed by shaking the mercury out of the cup. An explanation of the constant results is

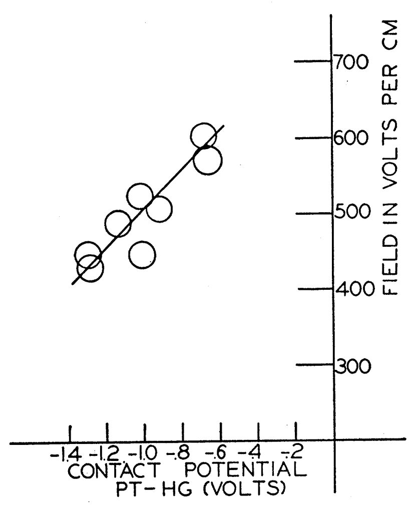

FIG. 4. Breakdown field *vs.* contact potential. The contact potential was measured with respect to a platinum filament.

that the surface was completely covered with a layer of impurities which did not flow off with the usual overflowing caused by distilling. The erratic results obtained when the surface was definitely changed indicated that the surface layer had been changed to a layer of patches, since the contact potential measurements depended on the average value of the work function while the breakdown depended on the local condition immediately under the anode. These patches could easily be seen.

The data for Table II were taken on mercury which had been purified according to the process outlined by Roller.[9] Before the mercury was transferred to the system, the still and discharge tube were baked out at 350°–400°C, the vacuum system being torched out in the meantime. Liquid air was used on the traps.

Under the conditions the values were much more erratic than in the previous case, there being at no time any correlation between contact potential measurements and breakdown fields. This would seem to indicate that there were only impurities enough to form patches and not enough to cover the surface completely at any time.

The curve of Fig. 4 was obtained after the mercury had been further purified by distilling it four times in air at a pressure slightly less than one atmosphere. This caused thick films of oxide to be formed over the surface which were removed each time by pouring the mercury through a filter paper funnel. The process evidently removed most of the impurities so that there were not enough left to form patches. The tube was also again baked out at about 400°C for eight hours before the clean mercury was introduced into it. The mercury was further purified by vacuum distillation after it was placed in the system.

The curve is similar to that obtained by Quarles. It has almost the same slope, but extends to higher breakdown fields. The contact potentials are only relative so that his values cannot be compared with these. Neither can the values of Fig. 4 be compared with those given in the Tables, for different platinum filaments at different temperatures were used.

The reason for the breakdown fields being so much lower than those predicted by theory is not apparent. With the short impulses shown by the oscillograms, it is difficult to believe that they are due to error in measurement as a result of surface distortion of the mercury. According to the theory of Tonks, even if there were waves on the mercury surface of amplitude 8.3×10^{-5} cm before the application of the field, it would require a time of 1.5×10^{-5} sec. to cause rupture with the highest fields here used (7×10^5 volts/cm). The oscillograms show that the fields were applied for less than one-hundredth of this time. It is impossible to say whether disturbances of this magnitude were already present, but such disturbances would have to be due either to thermal agitation or to external mechanical causes. Mandelstam[10] has developed a theory for the roughness of liquid surfaces due to thermal agitation and, by means of light scattering, Gans[11] has tested the theory for liquid mercury surfaces finding that, at ordinary temperatures, the average roughness height is only of the order of 10^{-9} cm. No ripples could be observed on the surface and, during the experiment, mechanical vibrations were prevented by the air cushion mounting. It is therefore difficult to assume that the field measurements could be in error by a factor of approximately one hundred, which would be a necessary assumption in order to obtain agreement with theory.

It was found that the breakdown potentials were consistently higher if the wave fronts of the impulse were made steeper. On the average, the values were 4 or 5 percent higher, which cannot be attributed to distortional ripples since the same increase for solids has been found by Snoddy (unpublished). Moreover, this is accounted for by the finiteness of the time required to initiate a vacuum discharge.

In conclusion I wish to express my sincere appreciation to Dr. J. W. Beams for suggesting the experiment and for his continued interest and guidance. I also wish to express my appreciation to Dr. L. B. Snoddy for his assistance in taking the oscillograms and for the privilege of discussing this paper with him.

[9] Roller, J. Opt. Soc. Am. **18**, 357 (1929).

[10] Mandelstam, Ann. d. Physik **41**, 609 (1913).

[11] Gans, Ann. d. Physik **74**, 231 (1924).

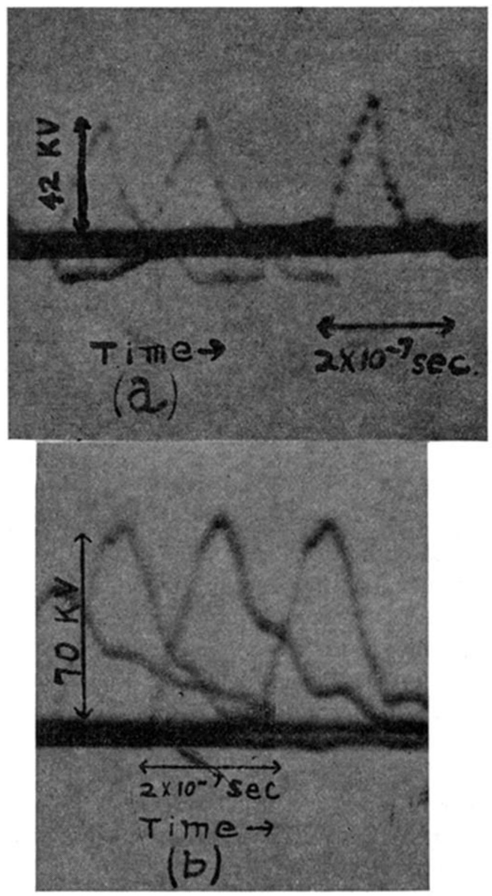

FIG. 2. Oscillograms of the impulse when the spark occurred (a) at the auxiliary gap, (b) at the vacuum gap.