Thermionic emission experiment using a phototube

Edgar Pearlstein, Gregory Swift,* and Kenneth Wright†
Department of Physics, University of Nebraska, Lincoln, Nebraska 68508
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An advanced undergraduate laboratory experiment is described for studying thermionic emission. The cathode of a type 922 photodiode is used as the emitter, over a temperature range from room temperature to 80°C. The thermionic emission current varies by a factor of 3000 over this temperature range, enabling good determination of the work function of the cathode, which can be compared with the photoelectric work function. The experiment requires no specialized apparatus.

I. INTRODUCTION

This article describes an undergraduate laboratory experiment in thermionic emission. The novel feature is the use of the dark current of a phototube, in a temperature range that can be measured with an ordinary mercury thermometer. Data are taken of dark current versus voltage, for a number of temperatures. Analysis of the data yields the work function of the cathode.

A previously described experiment[1] uses a tungsten cathode that is electrically heated to incandescence. That experiment has the advantage that the emitter is a pure metal, but the disadvantage that the temperature is inferred by the resistance of the tungsten, rather than by "direct" measurement. More recently, some experiments have been described[2,3] which use commercial vacuum tubes with oxide-coated cathodes. These experiments study a number of aspects of thermionic emission, including the distribution of electron velocities, but the cathode temperature must be inferred from that distribution.

II. EXPERIMENTAL ARRANGEMENT

Thermionic emission is studied in an RCA type 922 phototube (available from electronics supply companies for about $6). This tube is sensitive to light into the near infrared (*S*1 response), with a cathode work function of about 1 eV. The cathode and anode connections come out of opposite ends of the glass envelope, which enables effective precautions against leakage currents.

Figure 1 shows the electrical circuit for measuring dark current versus voltage. The guard ring is merely a strip of conductive paint applied to the outside of the glass and grounded. Without it, there is enough leakage current either through or on the surface of the glass to completely mask the thermionic current. As will be seen from the data, the guard ring does not completely stop leakage current from getting to the electrometer, but it keeps it sufficiently small that one can distinguish between true thermionic current and leakage current by assuming that the former saturates with voltage, while the latter obeys Ohm's law. (We suggest that it would be instructive for students to measure the current both before and after applying the guard ring.)

It is absolutely necessary that the phototube and the signal wire to the electrometer be well shielded against electrostatic pickup. Ordinary coaxial cable is not quite good enough (the braided shield has holes in it), but wrapping aluminum foil around it will make it satisfactory. A convenient test for the adequacy of shielding is to run a comb through your hair and bring it close to the wiring—any flaw in the shielding will show up immediately as a wild motion of the electrometer indicator. It is also necessary that the signal lead be prevented from vibrating because (assuming that coaxial cable is used) the conductors rub against the dielectric and generate charges.[4] Vibration is effectively prevented simply by taping the cable to the tabletop.

The phototube is placed in a large test tube, with the wires going through a rubber stopper, as shown in Fig. 2. A mercury thermometer also extends through the stopper. The test tube is covered with aluminum foil, which is both an electrostatic and a light shield. The test tube is immersed in a water bath whose temperature can be varied. In our case, this was a coffee can into which preheated water was poured. Each time the water temperature was changed, it required just a few minutes for the photocathode to reach its equilibrium temperature.

One useful pedagogical result of this experiment is that students observe through their own actions how attention to simple details of shielding and light tightness can make an orders-of-magnitude difference in useable sensitivity.

III. DATA

Figures 3 and 4 show current–voltage curves for two temperatures, which are the lowest and highest used in this particular run. Note that the current rises in a "saturation" manner at low voltages, then linearly, and then, at voltages higher than about 150, rapidly. We attribute these behaviors respectively to saturation of the thermionic emission current, residual electrical leakage which obeys Ohm's law, and field-enhanced thermionic emission.[5] We will ignore the latter effect here, but it could be an interesting subject for an extension of this experiment.

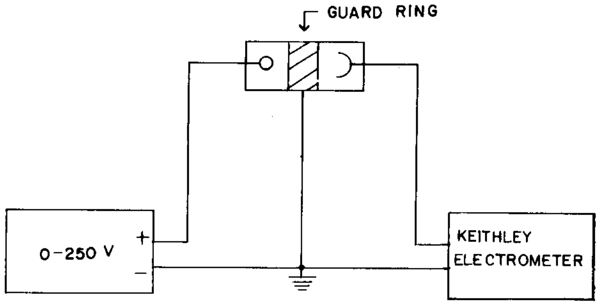

Fig. 1. The circuit. The guard ring is conducting paint applied to the glass of the phototube. The Keithley electrometer can measure currents down to 10^{-13} A.

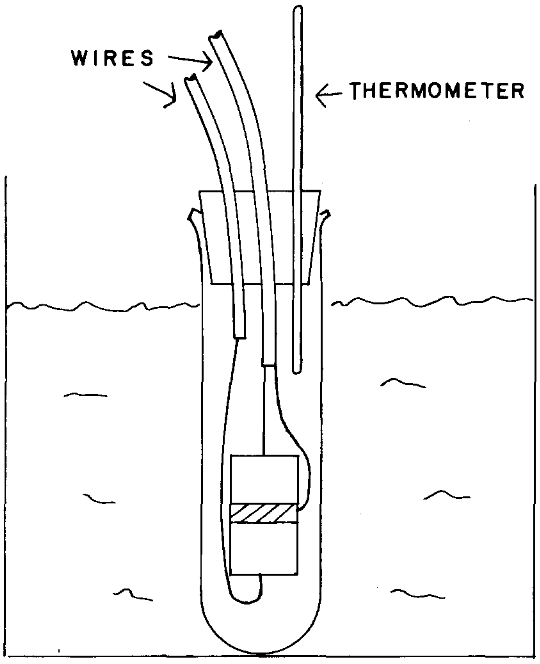

Fig. 2. Arrangement of the apparatus. The phototube is placed in a large test tube, which is covered with aluminum foil for electrostatic and light shielding. The wires and a thermometer leave the test tube through a rubber stopper. The tube is immersed in a water bath.

As shown in Figs. 3 and 4, the linear parts of the curves are extrapolated to zero voltage, and this gives the saturated thermionic currents according to the following reasoning: We assume that the straight-line portion of the data represents saturation current plus Ohm's law leakage current. If we write this part of the data $I = a + bV$, then b is the leakage conductance and a is the thermionic current. Thus, extrapolating the straight line to zero voltage, as in Figs. 3 and 4, gives the saturated thermionic current.

IV. ANALYSIS

The free-electron model[5] of a metal predicts that the saturation thermionic current should obey Richardson's equation

$$J_s = AT^2 \exp(-E/kT), \tag{1}$$

where J_s is the saturation current per unit area of the cathode, T is the absolute temperature, k is Boltzmann's constant, and E is the work function of the cathode. The constant A is predicted to be the same for all metals:

$$A = 4\pi emk^2/h^3 = 120 \text{ A/cm}^2 \text{ K}^2, \tag{2}$$

where e and m are the charge and mass of the electron, and h is Planck's constant. [For semiconductors and insulators, the analog of Eq. (1) would still have the exponential factor, but the preexponential part would depend on the material and would have slightly different temperature dependence.]

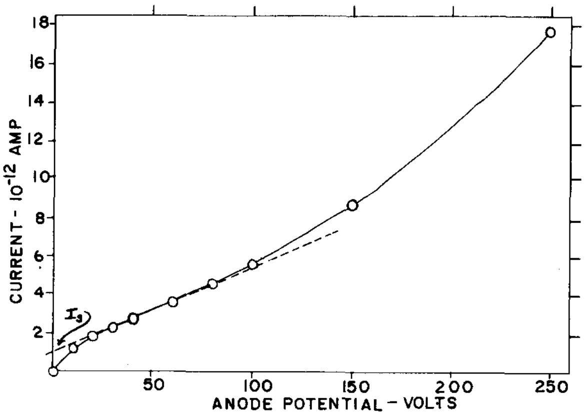

Fig. 3. Dark current versus voltage for the type 922 phototube. Temperature, 25 °C. The extrapolation to zero voltage gives what we interpret as the true thermionic current.

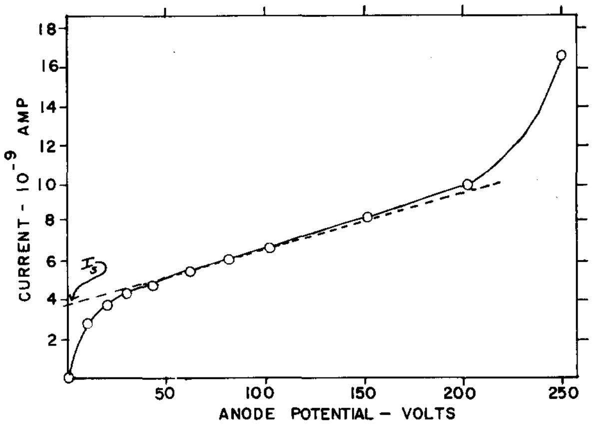

Fig. 4. Same as Fig. 3, but for a temperature of 78 °C.

The data to be analyzed consist of saturation current, I_s, as a function of temperature. We see from Eq. (1) that a graph of $\log(I_s/T^2)$ vs $1/T$ should yield a straight line, from whose slope and intercept one can determine E and A. Table I gives data, and Fig. 5 shows them plotted.

Several things about Fig. 5 should be noted: (a) The data

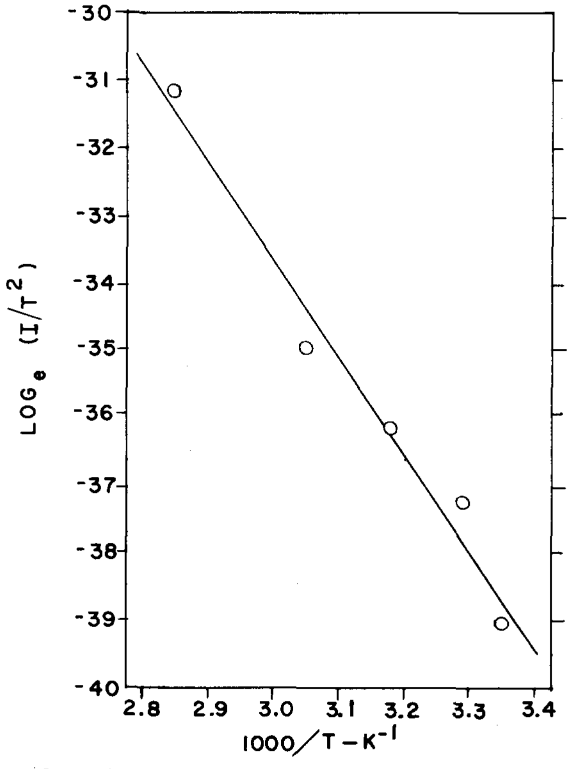

Fig. 5. Saturation thermionic current versus absolute temperature. Data are from Table I. The straight line is determined from an unweighted least-squares fit. Its slope gives for the work function 1.25 ± 0.09 eV.

do seem to fit a straight line, in accordance with Richardson's equation. (b) The T^2 part of Richardson's equation cannot be said to have been verified by the data, since the major temperature dependence is in the exponential part of the equation. (c) Although the extrapolation procedure for finding the saturation currents (Figs. 3 and 4) is not very precise, the total range of current is more than a factor of 3000, and since it is the logarithm of I_s that counts in determining E, even a factor-of-2 uncertainty in I_s is of only moderate importance.

From the slope of the graph in Fig. 5, we get for the work function of the photocathode $E = 1.25 \pm 0.09$ eV. This would give a photoelectric "cutoff" at 9900 Å. The RCA tube handbook shows for the type $S1$ response that the photoelectric sensitivity does not have a very sharp cutoff. Its peak is at 7500 Å, and it is down to about 6% of its peak at 9900 Å. We did not measure the wavelength sensitivity of our particular tube.

The infinite-temperature intercept of Fig. 5 should yield a value for the constant A in Eq. (1). From the least-squares-fitted line of Fig. 5 we get $\ln A = 8.7 \pm 3.4$, from which $A = 6000$ A/cm^2 K^2, with an uncertainty of a factor of 30. (This calculation uses, for the area of the emitting surface, 4.3 cm^2.) Because of the enormous uncertainty, this cannot be said to disagree with the free-electron theory value given in Eq. (2). In any case, though, there are a number of reasons[5] why one should not expect real metals to give a value of A in agreement with Eq. (2). In fact, we do not even know whether the cathode of the phototube should be considered to be a metal.[6] Fowler[7] gives a number of examples of experimental values for A.

V. CONCLUSION

The experiment requires no expensive apparatus other than that usually found in an advanced physics laboratory, and the phototube is inexpensive.

In addition to getting some familiarity with an important phenomenon, students should find this experiment valuable because of these features:

(1) Techniques of low-current measurement are used, including the use of a guard ring and other precautions.

(2) In the analysis of data one must subtract out the unwanted part of the current (leakage) by using theoretical guidance (Ohm's law).

(3) Graphical analysis of nonlinear behavior is used to find constants.

(4) There are some lessons in the propagation of errors: the work function can be determined well even though there is poor accuracy in current measurement, but the constant A requires good accuracy.

Table I. Data of saturation current versus temperature. The saturation current was determined as indicated in Figs. 3 and 4. The temperatures listed are the averages of those at the beginning and end of the particular runs of I versus V. The worst case of temperature drift was at the highest temperature, where the temperature changed by 2.5 °C during the run.

Temperature, T		1000/T	Saturation current, I_s (A)
°C	°K	°K^{-1}	
25.0	298.2	3.35	1.0×10^{-12}
31.2	304.4	3.29	6.2×10^{-12}
41.0	314.4	3.18	2.0×10^{-11}
55.1	328.3	3.05	7.2×10^{-11}
78.2	351.4	2.85	3.7×10^{-9}

(5) The experiment can be regarded as "open ended," in that students may, if they wish, attempt to test whether the high-voltage behavior of the thermionic current is consistent with the theory of field-enhanced emission, they can measure the photoelectric behavior of their particular tube, and they can attempt to calculate theoretically what thermionic work function to expect when the photoelectric work function is not sharply defined.

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[*] Present address: Department of Physics, University of California, Berkeley, CA.

[†] Present address: Department of Physics, Iowa State University, Ames, IA.

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