APPARATUS AND DEMONSTRATION NOTES

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This department welcomes brief communications reporting new demonstrations, laboratory equipment, techniques, or materials of interest to teachers of physics. Notes on new applications of older apparatus, measurements supplementing data supplied by manufacturers, information which, while not new, is not generally known, procurement information, and news about apparatus under development may be suitable for publication in this section. Neither the *American Journal of Physics* nor the Editors assume responsibility for the correctness of the information presented. Submit materials to Jeffrey S. Dunham, *Editor*.

Photoelectric effect experiment with computer control and data acquisition

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This note shows how to take reverse currents into account in a vacuum phototube and to measure stopping potentials more reliably with a computer data-acquisition system. The work function of the emitter is determined from the photoemission threshold.
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The determination of the ratio h/e from the photoelectric effect is a cornerstone experiment for introducing students to quantum physics. It is based on the Einstein equation

$$hf = \varphi + 1/2mv_{\mathrm{m}}^2, \tag{1}$$

where h is Planck's constant, f is the frequency of the incident light, φ is the work function of the emitter, m is the electron mass, and v_{m} is the maximum velocity of electrons leaving the emitter.

Many papers have been published on this experiment, and only a fraction of them are mentioned here. Hanson and Clotfelter[1] presented an evaluation of equipment available commercially for determining the ratio h/e in student laboratories. The authors stressed that certain practical problems encountered in this experiment make accurate results difficult to obtain. In particular, a serious problem is caused by the emission of electrons from the collector. The Leybold h/e apparatus includes a vacuum phototube with a collector in the form of a platinum wire loop that can be heated shortly before taking data. The purpose of the heating is to vaporize any material from the emitter that has condensed on the collector. It turned out that the results obtained depended strongly on this procedure. It was shown[2] that the work function of the emitter entering the Einstein equation should be replaced by the work function of the collector. Powell[3] justified a procedure often used to determine the stopping potential from a plot of the square root of the photocurrent versus applied bias voltage. Steinberg *et al.*[4] developed a computer-based tutorial on the photoelectric effect.

To determine the ratio h/e, one needs to measure the cutoff energy, i.e., the stopping potential, for several frequencies of incident light. Two distinct methods are known for this purpose. The first method repeats Millikan's observations of the *I-V* characteristics of a vacuum phototube. The second method employs an open circuit phototube and allows the collector to charge negatively until no more electrons can reach it. This self-induced bias is measured as a function of the frequency of incident light; however, it was shown[5] that increasing the light intensity causes the cutoff energy to increase. This method is also used in student experiments.[6–8]

The Einstein equation is strictly correct when the emitter is at the absolute zero of temperature. At any finite temperature, the thermal motion of electrons in the emitter contributes to their initial velocities when leaving. Knudsen[9] has shown that one can solve the problem by applying Fowler's theory, which takes into account the emitter's temperature, and using the plane-parallel geometry of the electrodes. With these improvements, the results obtained were within 1% of the precise h/e value.

In most student laboratories, a commercial phototube is used for this experiment, and the results of such measurements may differ significantly from the expected value. The main reason for this disagreement is the reverse current through the phototube. The reverse current includes two independent contributions: a leakage current due to insufficient resistance of the glass of the phototube, and a current resulting from electrons emitted by the collector. The leakage current is proportional to the applied voltage and can be determined by measurements in the dark. For the electrons emitted by the collector, the potential applied to the phototube is an accelerating voltage, and the current saturates at low accelerating voltages. However, this is correct if the current is sufficiently small. If one introduces corrections for the leakage current, the *I-V* curve looks like an ideal one, but

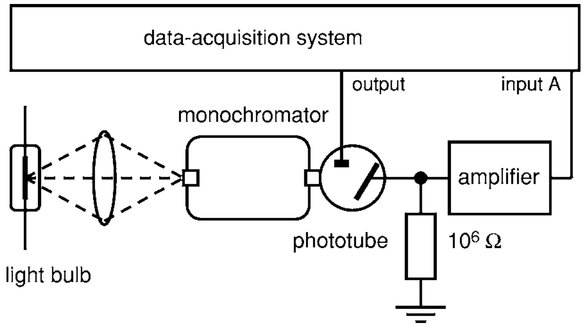

Fig. 1. Arrangement for determining stopping potentials with the computer data-acquisition system.

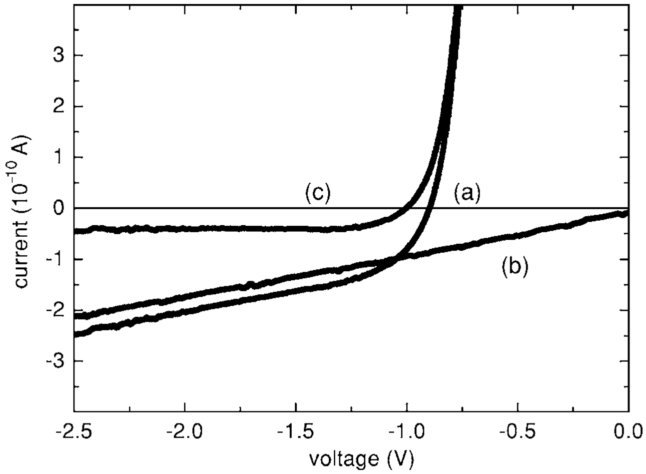

Fig. 2. Part of the phototube *I-V* characteristic for a light wavelength of 500 nm: (a) original data (smoothed), (b) contribution of the leakage current, and (c) data corrected for the leakage current.

instead of zero the current approaches a definite negative value. The stopping potential should be taken as a point where the corrected curve first begins to turn upward. Employment of a computer data-acquisition system has an important advantage because all of the characteristics can be obtained in a short time. This allows one easily to see and take into account the above-mentioned reverse-current phenomena and to determine the stopping potentials more reliably.

In our laboratory, a 1P39 vacuum phototube (also known as a 929 phototube) is illuminated by means of an incandescent light bulb and a grating monochromator, as shown in Fig. 1. As is common for this type of arrangement, the photocathode is masked with a piece of black tape. The load resistor of the phototube is $10^6\ \Omega$. The voltage across it is amplified by a Keithley model 177 multimeter and then fed to the input of a data-acquisition system, the PASCO's *ScienceWorkshop* with DATASTUDIO software. On the 20-mV scale, the multimeter provides 100-fold voltage amplification. A 0.001-Hz *Sine wave* voltage from the *Signal generator* is applied to the phototube. After starting the measurements, the generator starts to reproduce the negative part of this waveform, and one run lasts 250 s. The measurements are performed for wavelengths from 400 to 650 nm. The DATASTUDIO software allows the part of the characteristic close to the stopping potential to be enlarged. The *Smooth* option is useful to reduce the scatter of the experimental points. Without the illumination, the characteristic represents the leakage current (dark current) that is linearly dependent on the applied voltage. Using *Fit/Linear fit*, one determines this dependence and subtracts these data from those with illumination. Now the *I-V* characteristic contains only two contributions: the photoelectric current from the emitter, and that from the collector. The latter is small and reaches saturation at low voltages. By measurements of the photocurrent from the emitter, it was confirmed that saturation of currents comparable with those from the collector occurs at accelerating voltages less than 1 V. With the procedure proposed, the determination of the stopping potential becomes easier, as can be seen in Fig. 2. The uncertainty in the determination of the stopping potential is several hundredths of a volt. Also important is that students clearly see all three contributions to the current flowing through the phototube. Usually, the h/e ratio obtained is within ±5% of the precise value. An example of data obtained with our apparatus is shown in Fig. 3.

The simplest method for determining the work function of the emitter is a measurement of the longest wavelength of light for which the photoelectric effect is still possible. As can be seen from Eq. (1), the energy of quanta at the photoemission threshold is equal to the work function

$$hf_0 = \varphi. \tag{2}$$

This relation is strictly correct if the cathode is at the absolute zero of temperature.

The arrangement shown in Fig. 1 is used for the determination of the photoemission threshold. The phototube is connected to a 9-V battery, and the *Voltage sensor* measures the voltage across the load, a 10^6-Ω resistor. The measurement data are taken by DATASTUDIO every 10 s, which is sufficient time to change the wavelength setting of the monochromator manually. The data obtained are shown in Fig. 4. The photoemission threshold is approximately 0.7 μm, which coin-

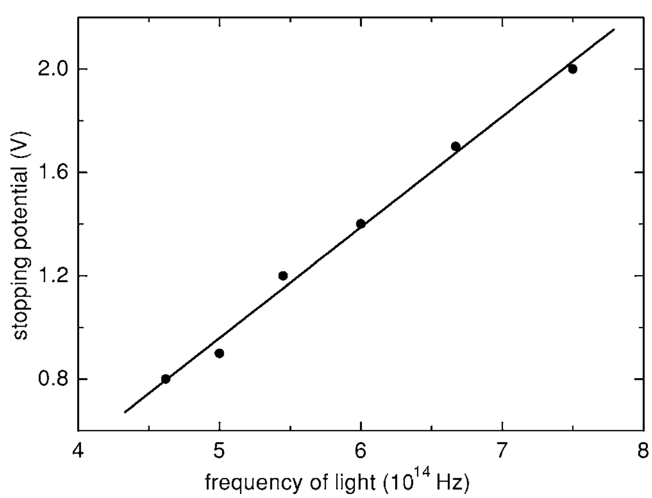

Fig. 3. The stopping potential vs the frequency of incident light. The slope of the straight line is the *h/e* ratio. For the example given, the slope equals 4.28×10^{-15} JsC^{-1}.

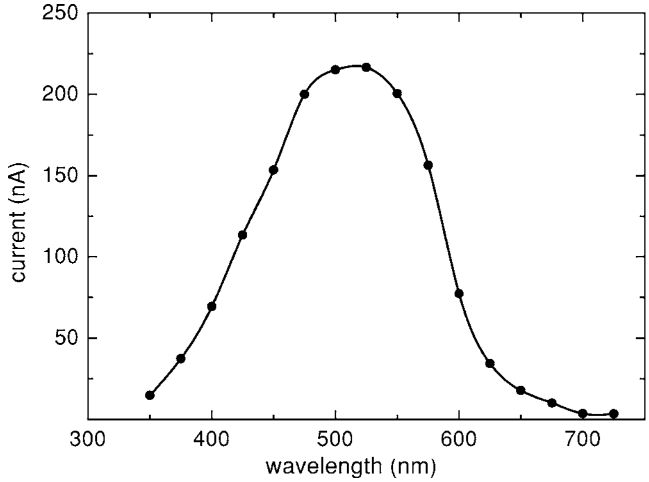

Fig. 4. The photoelectric current as a function of the wavelength of the incident light.

cides with that for the Cs-Sb cathode used in this phototube (the so-called S-4 response).[10] The work function φ thus equals 1.8 eV.

In conclusion, the procedure proposed is useful. The use of automated data acquisition makes the measurements easier, and all contributions to the current through a phototube are clearly seen.

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THE IMPORTANCE OF HYDROGEN

"We can say the world is the way it is because the laws of nature are the way they are. Or we can say that the world is the way it is because hydrogen is the way it is. Whichever you select, one or the other, is a matter of preference. Either way, the little hydrogen atom commands the stage on which the long and enchanting drama of our universe, the story of galaxies, stars, planets, and life, unfolds."

John S. Rigden, *Hydrogen: The Essential Element* (Cambridge University Press, Cambridge, Massachusetts, 2005), p. 11.