SELECTIVE EXPERIMENTS IN PHYSICS

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EXP. No. ....

THE PHOTOELECTRIC EFFECT

OBJECT: To study the characteristics of photoelectric tubes.

METHOD: The phototube, in series with a galvanometer, is connected to a potential divider which provides a potential difference between the emitter and the collector of the phototube. The photoelectric current is measured as a function of (a) the potential across the tube terminals, (b) the light intensity on the emitting surface, and (c) the wavelength of the incident light. The work function and the ratio of Planck's constant to the charge of the electron are computed from these data.

THEORY: When light of suitable frequency is incident upon certain metallic surfaces, the material emits electrons. This phenomenon was first observed by Heinrich Hertz in 1887. Later experimental investigation established three facts relating to the electron emission of a given photosensitive surface.

1. For any given material there is a minimum frequency (or maximum wavelength) of the incident light below which electrons will not be emitted. This frequency is called the *photoelectric threshold* of the emitting surface.

2. The number of electrons emitted per second (photoelectric current) is directly proportional to the intensity of the incident light.

3. The maximum velocity (or kinetic energy) of the emitted electrons depends only upon the frequency of the incident light and is independent of the intensity of the light. The wave theory of light is completely inadequate in accounting for these facts.

Light Quanta: In 1889, Max Planck made the very radical assumption that an atomic vibrator could absorb or emit energy only in finite amounts, or *quanta,* as a successful explanation of hot-solid radiation. The size of the quantum of energy, ε, is expressed by $\varepsilon = hf$, where f is the frequency of the oscillator and h is a universal constant. This constant is called Planck's constant and has the value $h = 6.62 \times 10^{-27}$ erg second.

Following this brilliant idea, which serves to explain the hot-solid radiation, Albert Einstein in 1905 pointed out that the Quantum Theory will also serve to explain the photoelectric effect. The basic idea of Einstein was that one photon, or quantum of electromagnetic radiation, caused the emission of one electron. Evidently, below the photoelectric threshold, the incident quantum of light has insufficient energy to release the electron from the metal surface. This minimal required energy is called the *work function,* ϕ, of the metal. At the threshold frequency the photon has an energy just equal to the work function of the surface, that is $\phi = h\,f_{(threshold)}$. At higher frequencies the photon energy is more than sufficient to release the electron and the excess energy appears as kinetic energy of the emitted electron. This theory fits the three experimental facts stated in the preceding section.

This idea of a quantum energy balance, which contributed to give Einstein the Nobel prize, is expressed in the equation,

$$\varepsilon = hf = \phi + \frac{mv^2}{2} \qquad (1)$$

The value of the work function, ϕ, is usually expressed in electron volts, where one electron volt $= 1.6 \times 10^{-12}$ erg.

Stopping Potential: The maximum kinetic energy of the electrons emitted by the photosensitive surface may be determined by applying a reverse potential V_s which just will prevent the released electrons from reaching the collector. Thus

$$e\,V_s = \frac{mv^2_{\max}}{2} \qquad (2a)$$

Substituting this value in Eq. 1, gives

$$e\,V_s = hf - \phi \qquad (2b)$$

Note that the stopping potential increases with increased frequency of the incident light.

Let V_s and V_s' be the stopping potentials for frequencies f and f' respectively, then

$$e\,V_s = h\,f - \phi \qquad (3a)$$

$$e\,V_s' = h\,f' - \phi \qquad (3b)$$

$$\text{and}\,\frac{h}{e} = \frac{V_s - V_s'}{f - f'} = \frac{\Delta\,V_s}{\Delta\,f} \qquad (3c)$$

Eq. 3a states that the slope of the curve (tangent value) plotted for values of V_s vs f gives the ratio of Planck's constant to the charge of the electron. Using the accepted value of either h or e, the other quantity may be computed.

The Phototube: The phototube is commonly constructed as shown in Fig. 1. The half cylinder emitter (cathode) is coated with an alkali metal which has a low work function. In use, the collector wire (anode) is made (+) relative to the cathode to draw the released electrons across the gap. In a vacuum phototube the glass envelope is carefully pumped free of all gases. In the gas phototube, a small

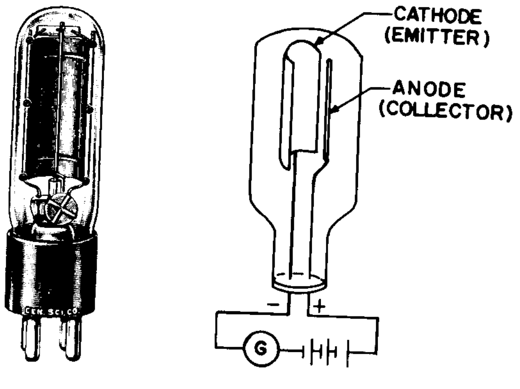

Fig. 1. Phototube.

quantity of gas is introduced into the glass envelope to increase the photoelectric current through ionization. The current may thus be amplified by a factor of 5 to 10 times.

When the emitter and collector surfaces are not alike, which is characteristic of a commercial phototube, there will be a contact potential, V_c, The applied stopping potential, V_a, is then related to V_s by $V_s = V_a + V_c$. However, when $V_a + V_c$ is substituted into Eq. 3c, one finds that

$$\frac{h}{e} = \frac{\Delta V_a}{\Delta f} \tag{3d}$$

In the construction of the phototube, the collector wire may also become coated and hence emit electrons. A tube of this type will show a photocurrent in a direction opposite its normal use when the potential is reversed on its terminals. To reduce the "collector" emission, the collector wire should be shielded from the incident light.

Assuming work functions ϕ and ϕ' for cathode and anode surfaces,

$$e\,V_c = \phi' - \phi \tag{4a}$$

Since

$$e\,V_s = hf - \phi = e\,(V_a + V_c) \tag{4b}$$

$$hf - \phi = e\,V_a + \phi' - \phi \tag{4c}$$

and

$$e\,V_a = hf - \phi' \tag{4d}$$

Spectral Response of Photoelectric Surface: The fact has been stressed that every photoelectric surface has its specific threshold value, that is, a maximum wavelength of incident light beyond which no emission occurs regardless of intensity. It must not be assumed, however, that all wavelengths of the incident light shorter than the threshold value are equally effective in releasing electrons. Each surface has its distinctive spectral response distribution, including peak values of emission for specific light frequencies. Figure 2 shows the spectral responses of two typical phototubes.

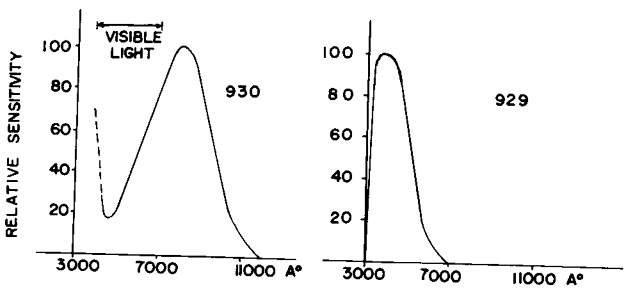

Fig. 2. Spectral Response of Phototubes.

Note that one of these phototubes is particularly adapted for use in the red and infrared region of the spectrum.

	PERCENT TRANSMISSION (APPROX.) FILTER NUMBER				
WAVE LENGTH A°	21	25	29	70	88
5000	. . .				
5200	. . .				
5400	3	. . .			
5600	60	. . .			
5800	84	2	. . .		
6000	88	55	. . .		
6200	89	83	39	. . .	
6400	90	86	80	. . .	
6600	90	88	89	13	. . .
6800	90	89	90	55	. . .
7000	90	90	90	79	5
			(12 AT 6100)	(1 AT 6500)	(1 AT 6900)

Table I. Transmission of Wratten Filters.

Light Filters: Light filters are used to transmit a desired type of radiation from a given source. Each filter has its characteristic transmission curve. Examples are shown in Figure 3 for Wratten No. 21 and No. 70 filters. The percentage transmission of the incident light by these filters for the frequencies expressed is given in the accompanying table, Table I. Note that the shortest wavelengths transmitted by these filters are approximately 5400 Å and 6500 Å respectively.

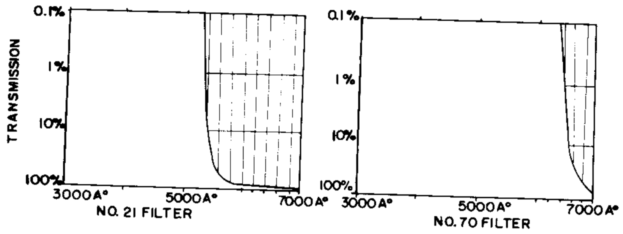

Fig. 3. Transmission Curves of Wratten Light Filters.

Figure 2 indicates that light transmitted by the No. 21 filter will release electrons from the cathode of either phototube. Light through the No. 88 filter is very effective in releasing electrons from the cathode of the No. 930 tube, but is near the threshold of the No. 929 phototube.

APPARATUS: Vacuum and gas phototubes (RCA 929 and 930); 120-volt dc and 2-volt dc sources; voltmeter (75/0.5 dc volts); 320-ohm rheostat; resistance box; galvanometer (Fig.

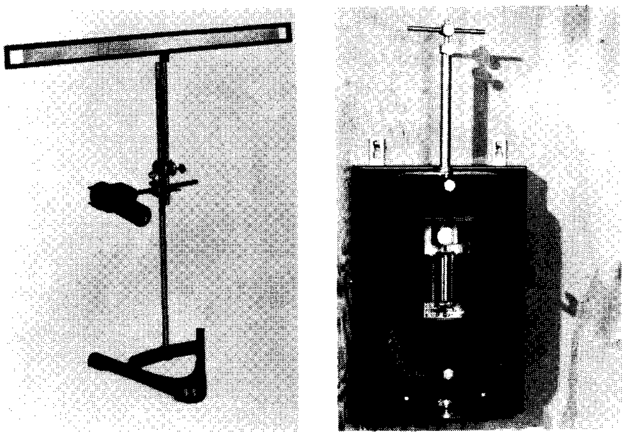

Fig. 4. Reading Scale and Galvanometer.

4) (approx. 0.008 μa/mm); 75-watt concentrated filament light source; DPDT switch; light tight box to house phototube and lamp; Wratten filters*.

*Filter No.	21	25	29	70	88
transmission $f_{max.}$ ($\times 10^{12}$ cy/sec)	556	517	492	461	435

PROCEDURE: The apparatus is connected as shown in Fig. 5. The galvanometer, *G*, is easily damaged so do not apply potential until your laboratory instructor has approved the circuit. The galvanometer should be adjusted to read zero on the left end of the scale. All readings must be made very carefully.

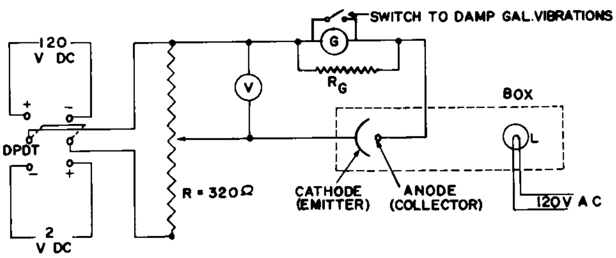

Fig. 5. Circuit of Phototube Experiment.

(A) *Variation of photoelectric current with applied phototube potential.* Place the vacuum phototube No. 929 in the light box with the lamp, *L*, at 50 cm from the tube. Apply 70 volts potential and adjust R_G for nearly full scale galvanometer deflection. Read the deflections for 70, 50, 30, 20, 10, 5, 3, 2, and 0 volts potential. Plot deflections vs voltage. Interpret the curve.

Repeat the above with the gas phototube No. 930 in the light box.

(B) *Variation of photoelectric current with intensity of surface illuminance.* Place the vacuum phototube No. 929 in the light box with the lamp *L* at 40 cm from the tube. Apply 70 volts to the phototube and adjust R_G for nearly full scale galvanometer deflection. Read the deflections with the lamp at distances *d* equal to 40, 50, 60, 80 and 100 cm from the phototube. Plot deflections vs $1/d^2$. Interpret the curve. The illuminance from a point source varies as $1/d^2$.

Repeat the above with the gas phototube No. 930 in the light box.

(C) *Effect of surface illuminance on stopping potential.* Replace R_G with a switch to be used to damp the galvanometer oscillations. Reverse the DPDT switch to connect the 2-volt cell as a stopping voltage on the phototube. Place the vacuum phototube No. 929 in the light box with the lamp *L* at 40 cm from the tube. Find the *minimum* stopping potential necessary to give zero photoelectric current. Repeat with the lamp at 30, 20 and 10 cm distances. Draw conclusions.

(D) *Effect of the frequency of the incident light on the stopping potential.* Place the lamp *L* near the phototube screened with one of the light filters. Use 2-volt cell. *Very carefully* determine the minimum value of the applied stopping potential to produce a zero galvanometer current. A strip of black opaque paper should be pasted over the tube to cast a full shadow on the collector pin. (Why?) Repeat the above for each filter provided.

Plot V_a vs f_{max} of the incident light.

Determine the experimental value of *h/e* from the slope of the above curve. Compare with the accepted value of *h/e*. ($h = 6.62 \times 10^{-27}$ erg sec.; $e = 4.80 \times 10^{-10}$ statcoulomb $= 1.602 \times 10^{-19}$ coulomb).

Extend the curve to find the experimental value of the threshold frequency.

QUESTIONS: 1. The wavelengths of the visible spectrum range from about 4000 Å (Violet) to 7000 Å (Red.). ($1 \text{ Å} = 10^{-8}$ cm). Silver has a work function of approximately 3.7 electron volts. Will it emit electrons when illuminated by visible light?

2. The photoelectric threshold wavelength of tungsten is 2.7×10^{-5} cm. What is its work function?

3. What will be the maximum velocity of electrons emitted from the surface of silver when it is illuminated by ultraviolet light of wavelength 2×10^{-5} cm?

4. X-rays are governed by quantum relations. They are produced when rapidly moving electrons strike the metal target. What would be the minimum x-ray wave length when the target (tungsten) is bombarded by electrons which have traversed a vacuum potential gap of 40,000 volts?

5. Phototube catalogs caution the user not to exceed a given potential between emitter and collector for a gas phototube. Why?

6. Assuming the answer of problem 4 to be 0.31 Å, what is the computed value of Planck's constant?

7. Compute the energy in a quantum of light from a sodium source which emits light of wavelength 5890 Å.

8. Your experimental value of *h/e* will deviate from the accepted value of 1.38 erg sec/statcoulomb. Discuss the contributing factors.