3.14 The Photoelectric Effect

Prelab Assignment 3.14

(1) What is photoelectric effect threshold frequency for a given element?

(2) What is work function for a given element?

(3) A sodium surface is illuminated with light of wavelength 0.300 μm. The work function for sodium is 2.46 eV. Calculate,

a. The energy of each photon in electron volts;

b. The maximum kinetic energy of the ejected photoelectrons;

c. The cutoff wavelength for sodium.

3.14.1 Introduction and Objectives

In the latter part of the 19th century, experiments showed that light incident on certain metallic surfaces caused the emission of electrons from the surfaces. This phenomenon is known as the *photoelectric effect*, and the emitted electrons are called *photoelectrons*. The first discovery of this phenomenon was made by Hertz in 1887. This photoelectric effect was unexplained until Einstein connected this experimental curiosity with Planck's idea that radiation comes in small packets, or quanta. In 1905, he proposed that the energy of the ejected electrons is proportional to the energy of the incident light with a constant offset that is unique to the metal, referred to as the work function. This phenomenon was a crucial precursor to the formulation of quantum mechanics as it was one of the first to show the wave-particle duality of light. Albert Einstein received the 1921 Nobel Prize in Physics for his services to theoretical physics and especially for his discovery of the law of the photoelectric effect.

After performing this experiment and analyzing the data, you should be able to:

(1)Test the Einstein's law of the photoelectric effect.

(2)Extract values for Planck's constant.

3.14.2 Required Equipment

- Mercury-arc lamp(Fig. 3.14-1)
- Light filter
- Photoelectric effect measurement apparatus

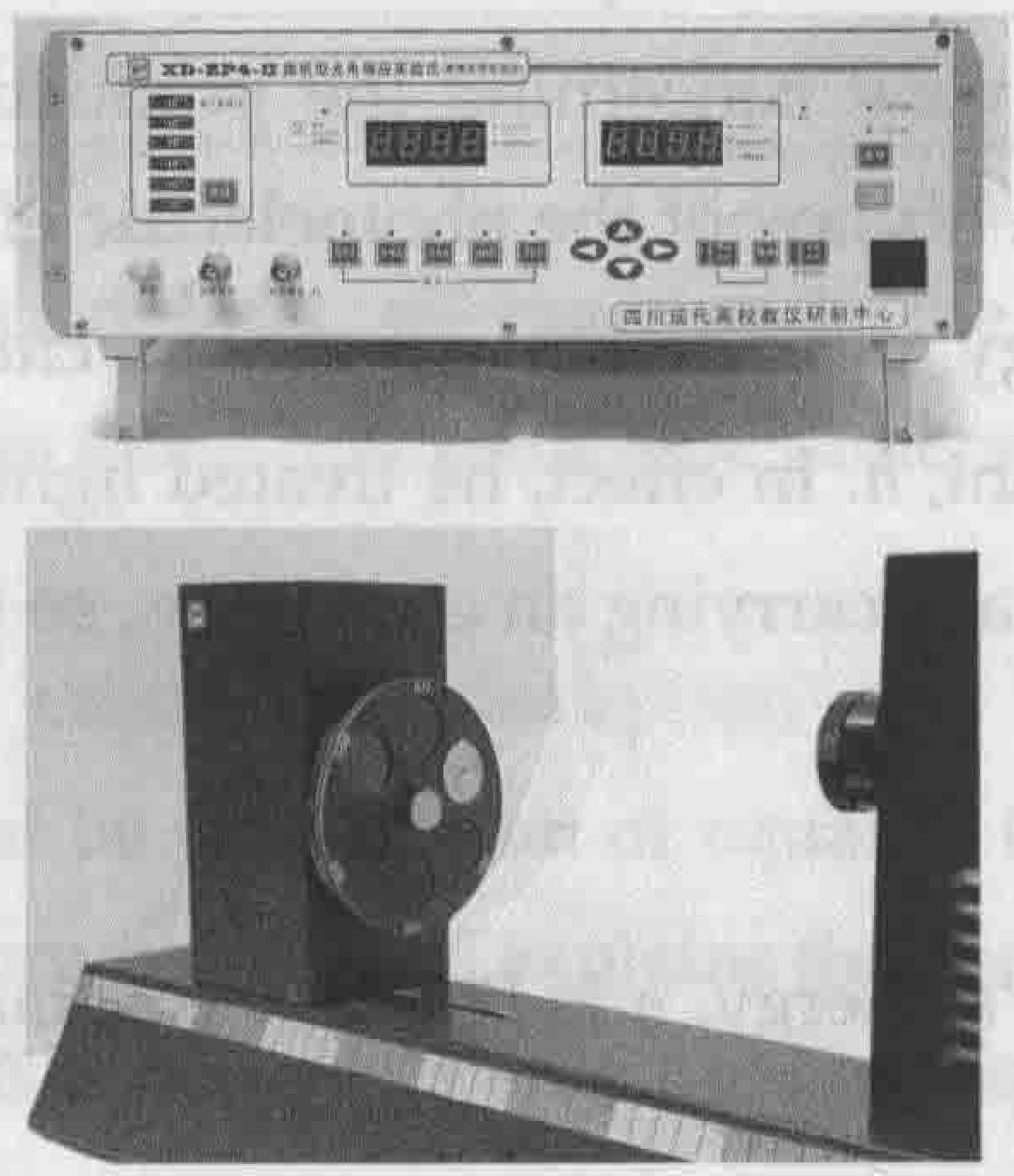

Fig. 3.14-1 Photoelectric effect apparatus

3.14.3 Theory

There are several features of the photoelectric effect that can't be explained with classical physics or with the wave theory of light:

(1)No electrons are emitted if the incident light frequency falls below some cutoff frequency f_c, also called the threshold frequency, which is characteristic of the material being illuminated. This fact is inconsistent with the wave theory, which predicts that the photoelectric effect should occur at any frequency, provided the light intensity is sufficiently high.

(2)The maximum kinetic energy of the photoelectrons is independent of light intensity. According to wave theory, light of higher intensity should carry more energy into the metal per unit time and therefore eject photoelectrons having higher kinetic energies.

(3)The maximum kinetic energy of the photoelectrons increases with increasing light frequency. The wave theory predicts no relationship between photoelectron energy and incident light frequency.

(4)Electrons are emitted from the surface almost instantaneously (less than 10^{-9} s after the surface is illuminated), even at low light intensities. Classically, we expect the photoelectrons to require some time to absorb the incident radiation before they acquire enough kinetic energy to escape from the metal.

Motivated by these, Einstein produced one of his seminal papers in 1905, "A heuristic point of view concerning the production and transformation of light", which put forth his law of the photoelectric effect. He extended Planck's notion that the energy of radiation comes in chunks of the frequency, v multiplied by a constant, h. In effect, he treated light as if it were composed of particles, or photons, each carrying an energy hv, so that

$$E = hv \tag{3.14-1}$$

where E is the photon's energy, h is Planck's constant and v is the frequency of the light.

The key point here is that the light energy lost by the emitter, hv, stays sharply localized in a tiny packet or particle called a photon. In Einstein's model a photon is so localized that it can give *all* its energy hv to a single electron in the metal. According to Einstein, the maximum kinetic energy for these liberated photoelectrons is

$$E_{\mathrm{K\,max}} = hv - w \tag{3.14-2}$$

where E_{Kmax} is the maximum kinetic energy for the photoelectron, w is called the work function of the metal. The work function, which represents the minimum energy with which an electron is bound in the metal, is on the order of a few electron volts. Table3.14-1 lists work functions for various metals.

Table 3.14-1 Work functions (w) for some selected metals

Metal	w/eV
Ag	4.73
Al	4.08
Cu	4.70

Continued

Metal	w/eV
Fe	4.50
Na	2.46
Pb	4.14
Pt	6.35
Zn	4.31

With the photon theory of light, we can explain the previously mentioned features of the photoelectric effect that cannot be understood using concepts of classical physics:

(1)Photoelectrons are created by absorption of a single photon, so the energy of that photon must be greater than or equal to the work function, else no photoelectrons will be produced. This explains the cutoff frequency.

(2)From Eq. (3.14-2), E_{Kmax} depends only on the frequency of the light and the value of the work function. Light intensity is immaterial because absorption of a single photon is responsible for the electron's change in kinetic energy.

(3)Eq. (3.14-2) is linear in the frequency, so E_{Kmax} increases with increasing frequency.

(4)Electrons are emitted almost instantaneously, regardless of intensity, because the light energy is concentrated in packets rather than spread out in waves. If the frequency is high enough, no time is needed for the electron to gradually acquire sufficient energy to escape from the metal.

Figure 3.14-2 is a schematic diagram of a photoelectric effect apparatus. An evacuated glass tube known as a photocell contains a metal plate K (the emitter) connected to the negative terminal of a variable power supply. Another metal plate, A (the collector), is maintained at a positive potential by the power supply. When the tube is kept in the dark, the ammeter reads zero, indicating that there is no current in the circuit. When plate K is illuminated by light having a wavelength shorter than some particular wavelength that depends on the material used to make plate K, however, a current is detected by the ammeter, indicating a flow of charges across the space between K and A. This current arises from photoelectrons emitted from the negative plate K and collected at the positive plate A.

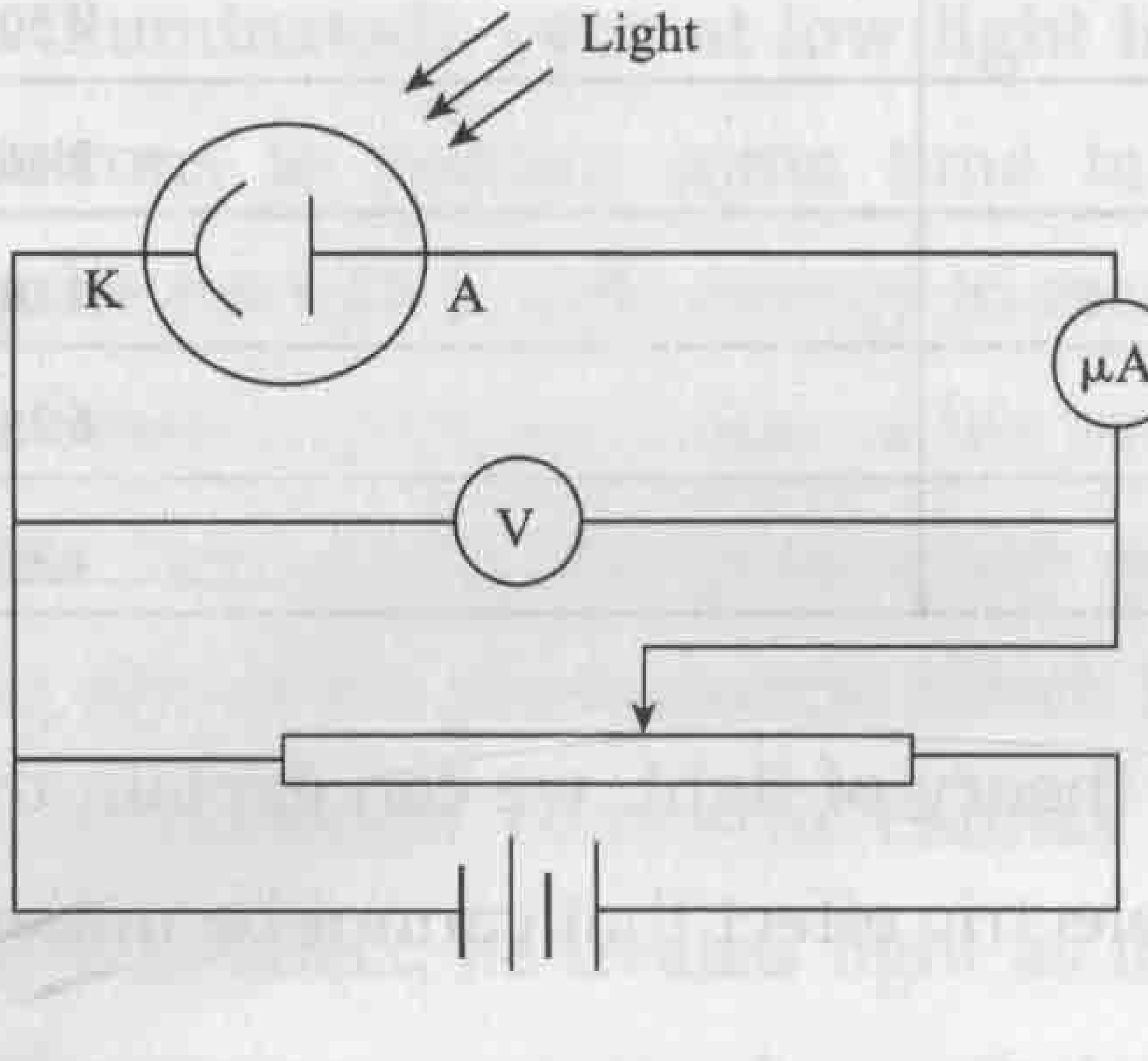

Fig. 3.14-2 A schematic circuit diagram for studying the photoelectric effect

Figure 3.14-3 is a plot of the photoelectric current versus the potential difference ΔV between K and A for two light intensities. At large values of ΔV, the current reaches a maximum value. In addition, the current increases as the incident light intensity increases, as you might expect. Finally, when ΔV is negative—that is, when the power supply in the circuit is reversed to make K positive and A negative—the current drops to a low value because most of the emitted photoelectrons are repelled by the now negative plate A. In this situation only those electrons having a kinetic energy greater than the magnitude of $e\Delta V$ reach A, where e is the charge on the electron.

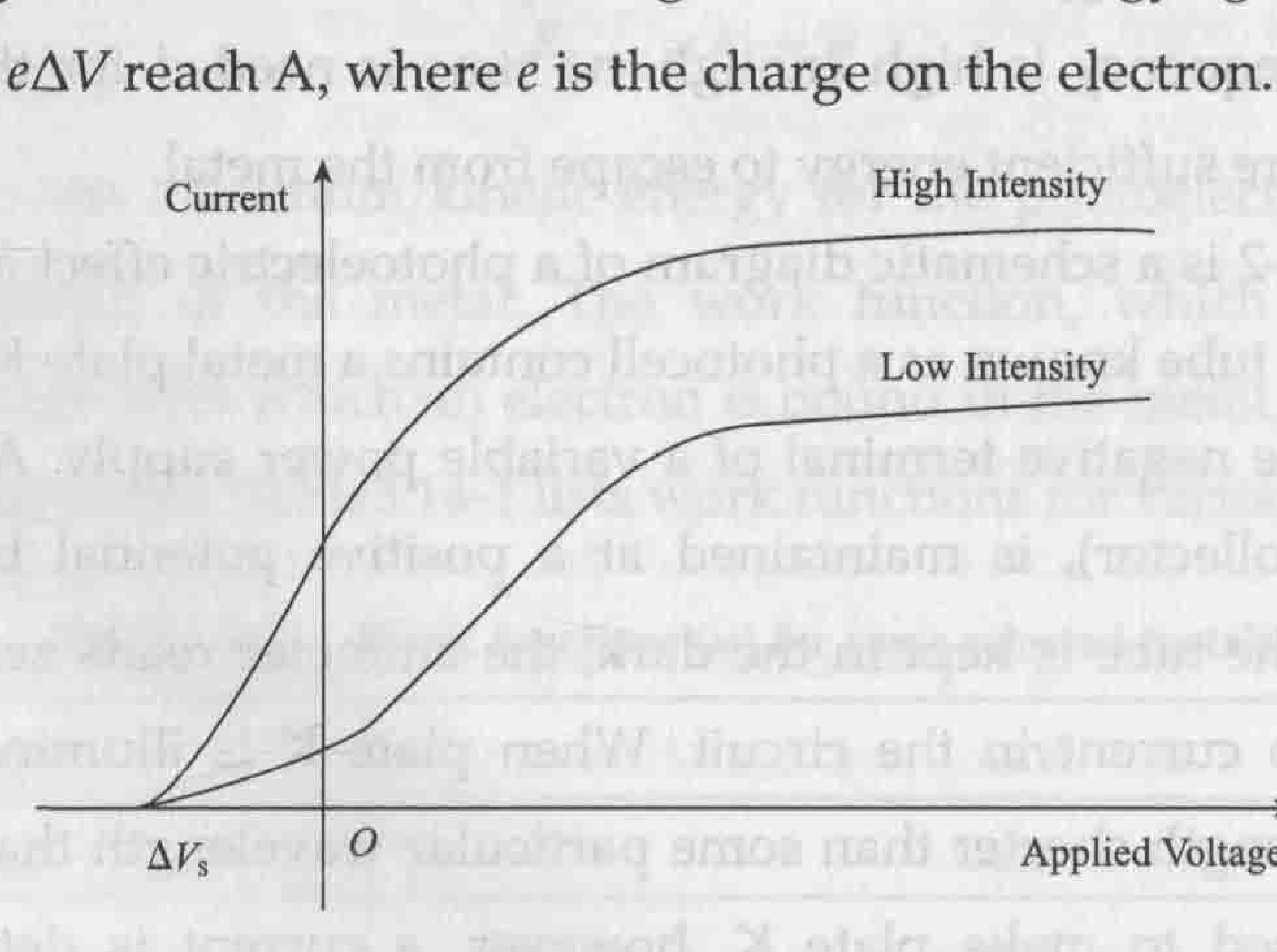

Fig. 3.14-3 Photoelectric current versus applied potential difference for two light intensities

When ΔV is equal to or more negative than ΔV_s, the stopping potential, no electrons reach A and the current is zero. The stopping potential is independent of the radiation intensity. The maximum kinetic energy of the photoelectrons is related to the stopping potential through the relationship

$$E_{\mathrm{K\,max}} = e\Delta V_{\mathrm{s}} \tag{3.14-3}$$

Combining Eqs. (3.14-2) and (3.14-3), we have

$$E_{\mathrm{K\,max}} = e\Delta V_{\mathrm{s}} = h\nu - w \tag{3.14-4}$$

Thus,

$$\Delta V_{\mathrm{s}} = \frac{h}{e}\nu - \frac{w}{e} \tag{3.14-5}$$

If ΔV_s is plotted as a function of ν, Einstein's theory predicts a straight line with slope *h*/*e* and *y*-intercept – *w*/e. Thus we can find an empirical value for *h* and the work function *w* of our photocathode simply by measuring stopping voltages.

3.14.4 Experimental Procedure

3.14.4.1 Measuring the Stopping Potential

(1)First, familiarize yourself with the apparatus.

(2)Rotate the filter disk to cover the window of the photoelectric tube. Cover the window of the light source with a cap. Turn on the power of the light source and the photoelectric effect measurement apparatus. Preheat the light source for about five minutes.

(3)Select the ranges of 10^{-13}A and –2~0V for the ammeter and voltmeter, respectively. After preheating, tune the "zero" knob to set the current to zero and then press the "Calibration" button.

(4)Move the photoelectric tube to adjust the distance between the light source and photoelectric tube to about 40 cm. Uncover the light source.

(5)Rotate the filter disk to mount the 365 nm filter on the window of the photoelectric tube.

(6)Adjust the magnitude of the voltage to find a value which makes the current zero. That's the stopping potential. Record the voltage in Data Table 3.14-1.

(7)Select the filters of 405 nm, 436 nm, 546 nm, 577 nm. Repeat Steps (5) and (6) to find the stopping potentials for the different lights. Record the voltages in DataTable 3.14-1.

3.14.4.2 Measuring the Current-voltage Characteristics of the Photoelectric Tube

(1)Move the photoelectric tube to set the distance *d* between the light source and photoelectric tube to about 30cm.

(2)Select the ranges of 10^{-11}(or 10^{-12}) A and $-2\sim50$V for the ammeter and voltmeter, respectively.

Note: If you change the scale of the ammeter you need to tune the "zero" knob to set the current to zero when the photoelectric tube is covered.

Rotate the filter disk to mount the 577nm filter on the window of the photoelectric tube.

(3)Adjust the magnitude of the voltage to read the current registered on the ammeter. Record the current in Data Table 3.14-2.

(4)Move the photoelectric tube to adjust the distance *d* between the light source and photoelectric tube to about 40 cm. Repeat Step (4) to complete Data Table 3.14-2.

3.14.5 Experimental Data

Data table 3.14-1 ***Purpose*: To measure the stopping potentials for different lights**

Wavelength /nm	Frequency /Hz	Stopping potential /V
365		
405		
436		
546		
577		

Data Table 3.14-2 ***Purpose*: To measure current-voltage characteristics of the photoelectric tube**

$\Delta V/\mathrm{V}$	−2.0	0.0	2.0	4.0	6.0	8.0	10.0	12.0
$d = 30\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 35\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 40\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$\Delta V/\mathrm{V}$	14.0	16.0	18.0	20.0	22.0	24.0	26.0	28.0
$d = 30\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 35\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 40\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$\Delta V/\mathrm{V}$	30.0	32.0	34.0	36.0	38.0	40.0	42.0	44.0
$d = 30\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 35\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 40\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$\Delta V/\mathrm{V}$	46.0	48.0	50.0					
$d = 30\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 35\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								
$d = 40\mathrm{cm},\ I/\times10^{(\ \ )}\mathrm{A}$								

Student's name and number:______________ Instructor's initial:______________

3.14.6 Calculations

(1)Use the following formula to compute the frequencies of the five lights. Show one sample calculation and enter the data in Data Table 3.14-1.

$$\nu = \frac{c}{\lambda} \tag{3.14-6}$$

Where c is the speed of light ($c = 3.000\times10^{8}$ m/s), and λ is the wavelength of light.

(2)Suppose that the frequency ν and the stopping potential ΔV_s satisfy the relationship $\Delta V_s = k\nu + b$. Use the data in Data Table 3.14-1 and the least-squares fitting method to determine the values of the Planck's constant and the work function of the metal in the photoelectric tube. Calculate the relation coefficient [see Eq. (2.28)] to interpret how well the line fits the data.

3.14.7 Graphing

(1)Use the entries in Data Table 3.14-1 to draw a smooth line described by the data points.

(2)Use the entries in Data Table 3.14-2 to draw a graph of the voltage dependent current for the photoelectric tube illuminated by different intensities.

3.14.8 Post Lab Questions

(1)For a given light intensity, when the accelerating voltage increases, the photoelectric current increases and then reaches the saturation. Why?

(2)State what property of light is demonstrated by the photoelectric effect.

(3)How would you claim that the Einstein's equation is verified by the photoelectric effect experiment?