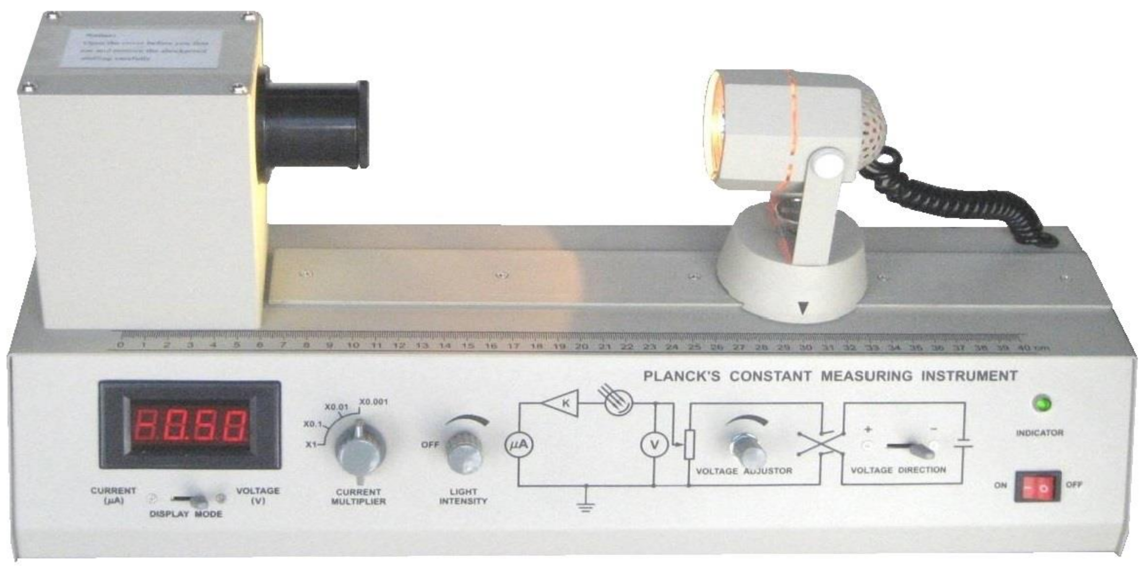
LEAI-50 Apparatus for Determining Planck's Constant– Basic Model

Instruction Manual



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1. Introduction

According to Einstein, light is emitted in the form of photons and the energy distribution of photons is not continuous (not governed by the Maxwell's electromagnetic theory). Rather, a photon has unit energy of "$h\nu$", where ν is the frequency of light and h is a constant. By illuminating a metal surface with light, the free electrons of the metal will absorb the photon's energy. If the photon's energy is higher than the barrier energy of the metal, electrons could escape from the metal surface. This effect is called the photoelectric effect. The kinetic energy of the escaped electron (i.e. photoelectron) will be:

$$E = h\nu - W_s \quad \text{or} \quad \frac{1}{2}m{v_m}^2 = h\nu - W_s \tag{1}$$

where h is Planck's constant (6.626×10^{-34} J·s), ν is the frequency of the illuminating light, m is the mass of an electron, v_m is the initial speed of the photoelectron at the metal surface, and W_s is the escape energy or the work function of the metal.

Equation (1) gives the maximum kinetic energy of the photoelectron without any obstruction in space. The higher frequency of the illuminating light is, the greater of the maximum kinetic energy of the photoelectron will be resulted, as seen in Fig. 1 (a). Considering the certain initial kinetic energy of the photoelectron, there may be some photoelectrons escaped from the metal surface (cathode) to form a photo-current even when no positive voltage is applied between the anode and the cathode. When such voltage is reversed at a certain value, photoelectrons can no longer reach the anode and hence the photo-current is zero at this time, as shown in Fig. 1 (b). This negative potential U_S is called as the cutoff voltage of the photoelectric effect, described by:

$$eU_s - \frac{1}{2}m{v_m}^2 = 0 \tag{2}$$

Substitute (2) into (1), we get

$$eU_s = h\nu - W_s \quad \text{or} \quad h\nu = \frac{1}{2}mv_m^2 + W_s \tag{3}$$

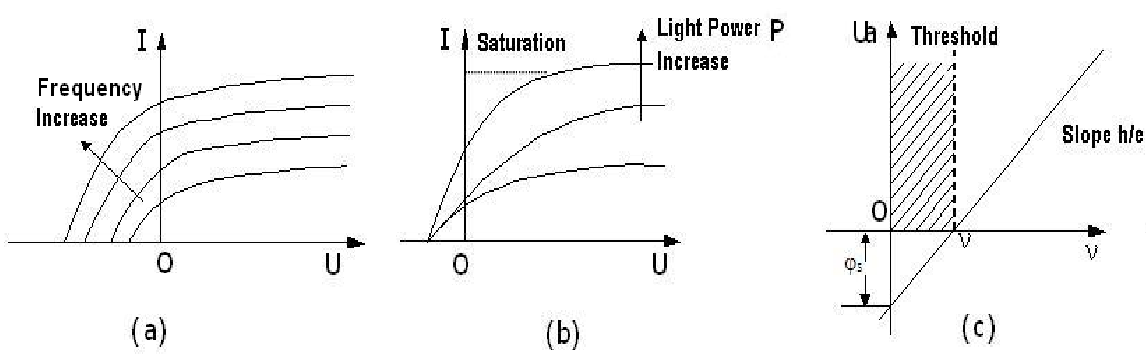


Figure 1 Dynamic energy of photoelectrons *versus* light frequency (a), photocurrent *versus* light power (b), and cutoff frequency of photoelectric effect (c)

Equation (3) is called the Einstein's equation, which states that no photocurrent is given when the photoelectron energy $h\nu$ is less than the work function W_s, as electrons cannot escape from the metal surface under such condition. For a given metal material, the minimum frequency of the illuminating light to create a photoelectric effect is $\nu_0 = Ws/h$, which is called as the cutoff frequency of the photoelectric effect (also known as the Red limit). Work function *Ws* is the inherent property of a metal material, which is independent of the frequency of the incident light. Equation (3) can be rewritten as:

$$U_s = \frac{h}{e}\nu - \frac{W_s}{e} = \frac{h}{e}(\nu - \nu_o) \qquad (4)$$

Equation (4) shows that the cutoff voltage U_s is a linear function of the frequency of incident light, ν. Obviously, $U_s=0$ when $\nu=\nu_0$, under such condition, there is no photocurrent. The slope of the straight line as described by Equation (4) is a constant k (= h/e), as shown in Fig. 1 (c), thus

$$h=ek \qquad (5)$$

where e is the electron charge (1.602×10^{-19} Coulombs).

Therefore, Planck's constant can be calculated by measuring the cutoff voltage U_s versus the frequency of illumination light, plotting the U_s - ν curve, and acquiring the slope k. **Note**: the illumination light does not need to have a single wavelength as only the cut-off wavelength (the maximum frequency) matters for the determination of the cut-off voltage (U_s). This is because the photoelectrons, released by light illumination at the cut-off wavelength, have the maximum kinetic energy. If the photoelectrons with the maximum kinetic energy can be stopped by the reverse potential, other photoelectrons with less kinetic energy can be stopped as well. Thus, a broadband light source such as Tungsten lamp with long-pass filters such as color filters can be used to measure Planck's constant based on Equation (4).

Figure 2 shows the experimental schematic of the photoelectric effect for determining Planck's constant using a photoelectric tube. When a light beam of frequency ν and power P illuminates the cathode of a phototube, photoelectrons escape from the cathode. If a positive potential is applied to the anode relative to the cathode, the photoelectrons will be accelerated; if a reverse potential is applied to the anode, the photoelectrons will be decelerated. The photocurrent will decrease with an increase in the reverse potential, U_{KA}. Finally, the photocurrent will be zero when $U_{KA}=U_s$. Figure 3 shows the typical *I-V* characteristic curve of a photoelectric tube.

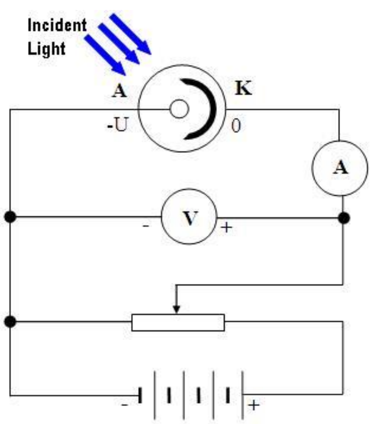


Figure 2 Experimental schematic

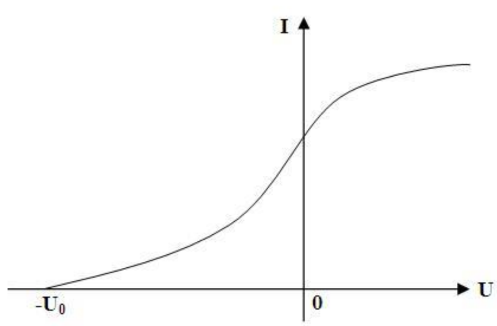


Figure 3 *I-V* characteristic curve

By illuminating a phototube with different light frequencies v, corresponding I-V curves of the phototube can be acquired, so that the corresponding cutoff voltages U_s of the phototube can be obtained. By plotting $U_s\sim v$ curve, an approximately straight line should be seen, as predicted by Einstein's photoelectric equation. Hence, Planck's constant h can be calculated from the slope k of the line using Eq. (5). In addition, the cutoff voltage U_0 of the cathode material can be found from the intersection of the I-V curve with the horizontal axis of the plot. Thus, the cutoff frequency v_0 can be achieved from U_0, which equals the electron escape potential Φ_S, as seen in Fig. 1 (c).

2. Specifications

1) Cut-off wavelengths of color filters: 635 nm, 570 nm, 540 nm, 500 nm, and 460 nm
2) Light source: 12 V/35 W Halogen Tungsten lamp
3) Sensor: vacuum phototube
4) Dark-current: less than 0.003 µA
5) Precision of accelerating voltage: less than ± 2%
6) Measurement error: less than ± 10% of (h=6.62619×10^{-34}J.s)

3. Structure

A schematic diagram of the apparatus is shown in Fig. 4. The apparatus consists of a light source, a light receiving phototube, a DC amplifier, and five color filters. The light source and the receiving unit are installed on the base rail, and their distance can be adjusted and read from the scale.

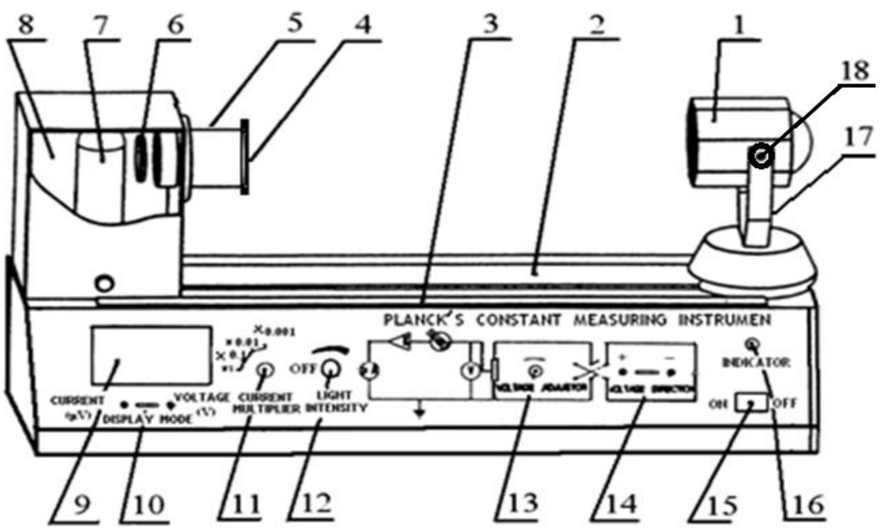


Figure 4 Schematic diagram of apparatus

1—Light source	2—Base rail	3—Scale (length= 400 mm)
4—Receiver cover (or filter)	5—Receiver tube	6—Focusing lens
7—Vacuum phototube	8—Receiver box	9—Digital meter (V or I)
10—Display mode switch (V or I)	11—Current multiplier	12—Light intensity adjust
13—Accelerating voltage adjust	14—Voltage polarity switch	15—Power switch
16—Power indicator	17—Locking screw	18—Fixing knob

4. Setup and Adjustment

Note: Upon receipt of the apparatus, unscrew the cover plate of receiver box (8) and remove protective sponge. Make sure the phototube is completely unobstructed and re-screw the cover plate.

Warning: Please handle the phototube and the light bulb with care, as they are very fragile!

1) Setup

a. Place the instrument on a secure table, make sure receiver tube (5) is blocked with cover (4), turn on the power, set light intensity adjustor (12) at moderate light level, slide light source (1) to 250 mm position, and tighten the lock screw (17). If the lamp is not turned on, check if the lamp bulb slips off the mount.

b. Adjust the tilt of the light source to let light illuminate straightly onto the phototube.

2) Electrical adjustment

a. Set display mode switch (10) to voltage display and adjust accelerating voltage adjustor (13) to get a stable voltage reading of ± 15 V.
b. Set display mode switch (10) to current display and keep the phototube covered while adjusting current multiplier (11) to choose among "×1", "×0.1", "×0.01", or "×0.001" to ensure the dark current is less than 0.003 μA.
c. Change light intensity adjustor (12) to view different light intensity levels among strong, moderate, weak, or off.
d. Optimal conditions: light should shine on the central area of the phototube's cathode plate rather than the anode, and maximum current should be observed. These conditions have been achieved in factory. If alignment is needed, open the top plate of receiver box (8) when the lamp is on, the image of the lamp can be seen on the cathode plate, adjust lamp location and tilt to bring the image to the central area of the plate (this should be performed by an experienced technician or instructor).

5. Experimental Procedures

1) Slide light source (1) to 250 mm position, turn on the power, pre-heat the system for 5 minutes, and set current multiplier (11) at "×1" position.
2) Place the red color filter (635 nm) onto receiver tube (5), set light intensity adjustor (12) at moderate light level, voltage polarity switch (14) at "+", current multiplier (11) at "×1" or "×0.1", and turn accelerating voltage adjustor (13) to gradually increase the photocurrent to saturation, and record the corresponding voltage. Use display mode switch (10) to toggle between current or voltage display.
3) Block the receiver tube by hand, the photocurrent should disappear at once; remove the hand, the photocurrent should reappear again, indicating that the photocurrent is formed very quickly (not exceeding 10^{-9} s).
4) Change the distance (*R*) between light source (1) and vacuum phototube (7), record the distance value (*R*) with corresponding photocurrent (*I*), and draw the I - $1/R^2$ curve. A straight line should be obtained.
5) Set light intensity adjustor (12) at strong light level, slide the light source to 300 mm position, voltage polarity switch (14) at "-", display mode switch (10) at current display,

accelerating voltage to 0 V, and set current multiplier (11) at "×0.001". Adjust the accelerating voltage to decrease the photocurrent to zero, write down the accelerating voltage value for 635 nm wavelength.

6) Repeat step 5) for each of the filters, and record the voltage value for each wavelength.
7) Convert the five wavelengths into frequencies ($\nu = c/\lambda$ where $c = 3\times10^8$ *m/s* is the speed of light), plot accelerating voltage versus frequency, calculate the slope of the plotted line by means of least-square curve fitting, and derive Planck's constant using Eq. (5).

Note: 1. To minimize measurement error, avoid or minimize stray light to the sensor.

2. To minimize the effect of dark current, the relationship curve between accelerating voltage and dark current should be acquired initially by measuring accelerating voltage with corresponding photo current with the receiver tube being blocked. Then, the acquired dark current should be used as the "zero" photo current when measuring the cutoff voltage in the experiment. For example, in the experiment, if the cutoff voltage of a specific filter is pre-determined at -0.5 V corresponding to real zero current output, and the dark current at this voltage is found 0.001 μA as previously measured, the accelerating voltage should be slightly adjusted until the photo current changes to 0.001 μA from 0 μA. In other words, the accelerating voltage corresponding to 0.001 μA should be taken as the cutoff voltage, rather than the accelerating voltage corresponding to zero current.

Warning: the Halogen Tungsten lamp can become very hot if turned on over a few minutes, so avoid touching the lamp or the lamp housing with bare hands!

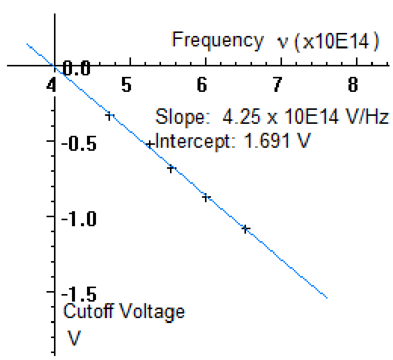
6. Example of Data Recording and Processing

Note: Following data are for reference purpose only, not the criteria for apparatus performance:

Cutoff voltages at various wavelengths are recorded in the table below:

Wavelength (nm)	460	500	540	570	635
Frequency (10^{14}Hz)	6.52	6.00	5.56	5.26	4.72
U_s (V)	**-1.08**	**-0.87**	**-0.68**	**-0.52**	**-0.33**

The Frequency – Cutoff Voltage relationship is plotted as following:



Planck constant is calculated as 6.803×10^{-34} J.s. Error is 2.7%.

7. Maintenance

The instrument should be operated at room temperature under controlled laboratory condition. When not in use, block the receiver tube with the black cover. The instrument should be stored in a dry and dust-free place.