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Photoelectric Effect Apparatus KSCIPEEA

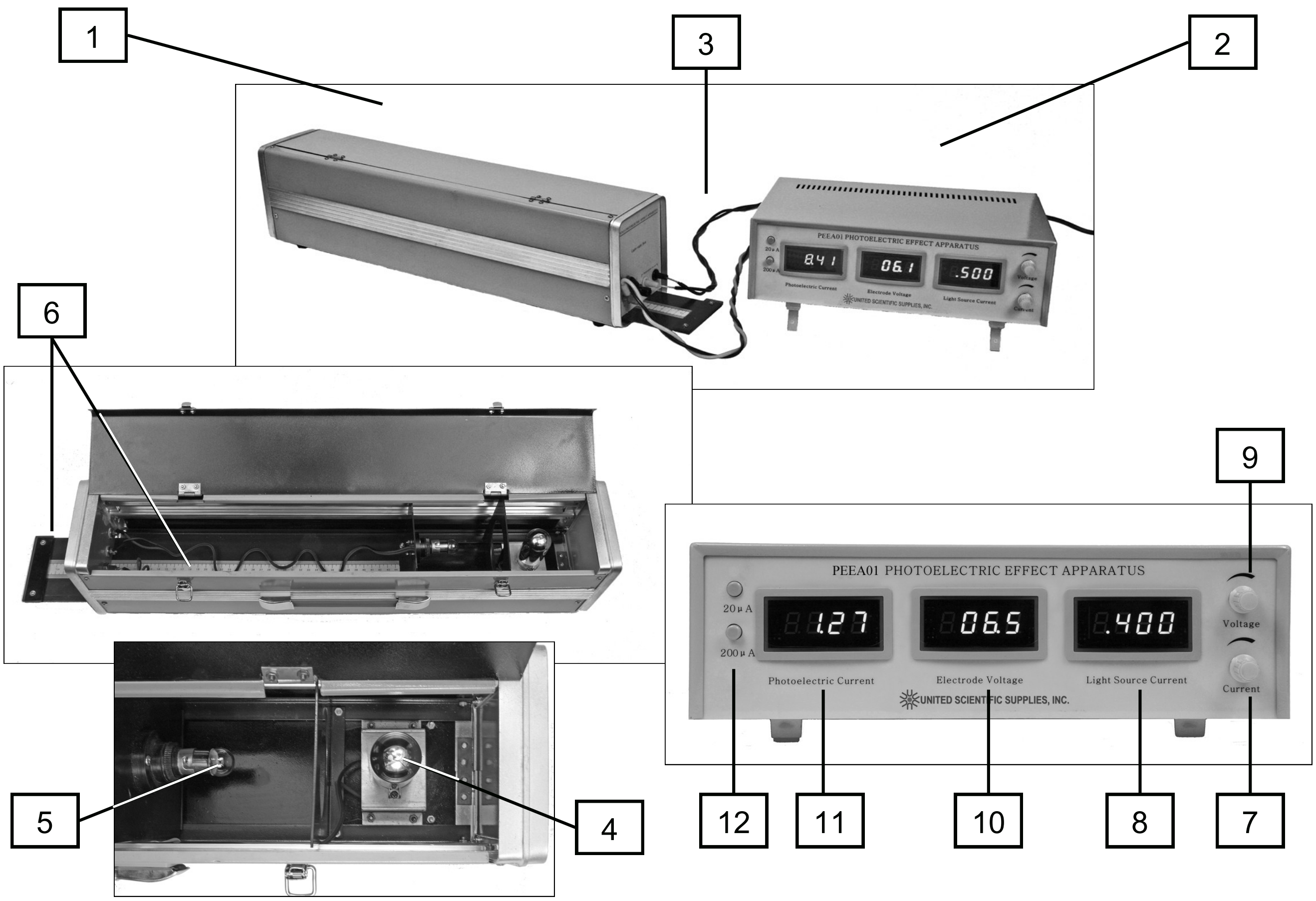

Figure 1

1. Description

The Photoelectric Effect Apparatus allows the photoelectric emission from a mixed metal cathode in vacuum to be studied as a function of the illumination and the extraction voltage applied. It consists of a light-tight box (1, *Figure 1*) connected to a control and measurement unit (2) by shielded cables (3). The light-tight box contains a vacuum phototube (4) with a Cs/Sb cathode and a current-controlled incandescent lamp (5) mounted on a slide (6) that is operated from outside the closed box to vary the illumination of the phototube. The control and measurement unit contains a highly stabilized lamp power supply adjusted by a multi-turn potentiometer (7). The current is indicated on a three-digit display (8). A second, independent, highly stabilized voltage source, also controlled by a multi-turn potentiometer (9), applies a precise d.c. extraction voltage to the phototube electrodes. The applied voltage is indicated on a three-digit display (10). The resulting photocurrent is measured by a sensitive amplifier and indicated on a 3-1/2-digit display (11) The amplifier gain has two ranges, selected by a pair of pushbuttons (12).

2. Specifications

Phototube:	Type GD-51 Mixed metal vacuum tube (Cs/Sb), 7-pin base		
	Rated voltage:	24V	
	Integral sensitivity (white light): 100μA/Lm		
Lamp:	Incandescent lamp, bayonet type, 12V/5W rating		
Control Unit:	Lamp supply:	0—15V, 185mA—665mA, on 10-turn potentiometer	
		Display resolution: 1mA	
	Electrode voltage supply:		-25.5V—+23.5V on 10-turn potentiometer
			Display resolution: 0.1V
	Photocurrent amplifier:		Ranges: 20 μA: 0—19.99 μA x 0.01 μA
			200 μA: 0—199.9 μA x 0.1 μA
	Fuse:	Miniature fuse, 5 x 20 mm, 250V/1.5A	
	Dimensions:	35 cm x 26 cm x 12 cm	
	Weight:	4.5 kg	
Light-tight Box:	Slide:	Range: 0.5 cm - 40.0cm, mm scale	
	Dimensions:	60.5 cm x 12 cm x 15 cm	
	Weight:	3.8 kg	
Connecting cords:	2 lamp supply cords, 75 cm long, spade lug/banana plug connectors.		
	2 shielded photocurrent cords, 75 cm long, BNC/banana plug connectors		
	1 Power cord, 2m long.		

3. Safety

- The control unit connects to a 110VAC outlet via a grounded plug. Observe all usual electrical safety precautions when operating it. In particular:
  - Do not use the apparatus if the cord or plug are damaged.
  - Do not use the apparatus in a wet or damp environment.
  - Do not defeat the grounding, which protects the user against dangerous external voltages in case of internal damage to the circuitry.
  - Make all changes to the connections with the apparatus **UNPLUGGED** from the 110VAC outlet.
- Only operate the apparatus under responsible supervision by a technically qualified person.
- To preserve the sensitivity of the phototube, always keep it in place in the light tight box and keep the box closed to minimize the tube's exposure to ambient light.

4. Theory

The photoelectric effect is the emission of electrons from the surface of a solid when it is illuminated with a beam of light. The light need not be visible; any electromagnetic radiation of sufficient energy can promote the effect. To study the photoelectric effect, the solid surface, usually metallic, is placed in a vacuum, because in a gas such as air, the emitted electrons quickly attach themselves to gas molecules and are difficult to control. The usual arrangement is a vacuum phototube with a photo-emitting cathode and an anode to collect the electron stream.

Consider the energy state of the electrons in a clean piece of metal placed in a vacuum. *Figure 2* shows this schematically. Taking the energy of a motionless electron in the vacuum conventionally as zero, the electrons bound in the metal's conduction band all have a lower energy and can be regarded as freely mobile in a "Fermi sea" of degenerate states whose highest energy level is the Fermi level. This is at an energy Φ below the vacuum level. Φ Is known as the work function. For an electron to leave the metal surface, it must be supplied with at least this energy.

Although the work function is a well-defined concept, it is notoriously difficult to measure in practice.

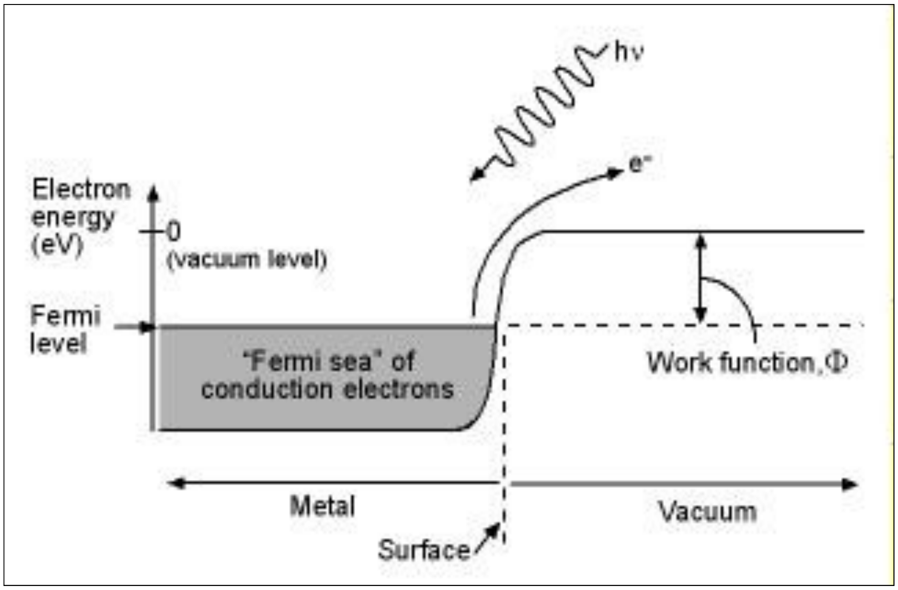

Figure 2

There are two main reasons for this. First, the value of Φ for clean surfaces varies with crystal orientation, so polycrystalline samples see an "average" value that varies a little depending on the crystalline state of the sample and second, in practice, the metal surface is rarely as clean as *Figure 2* suggests, even in a good vacuum. The surface is covered with oxides, adsorbed contaminants and gas molecules, all more or less loosely bound to the underlying metal atoms. These modify the smooth energy vs. distance curve shown in *Figure 2* and can increase or decrease the observed value of Φ, depending on whether they offer an electron state which is a "stepping stone" to the vacuum level or act as an electron trap.

When a photon strikes the metal surface and is absorbed, it delivers an energy packet $h\nu$ to the metal. If $h\nu \geq \Phi$, an electron can be ejected into the vacuum. For visible light in the wavelength range of 400 - 700 nm, $h\nu$ is 3.10 - 1.75 eV. For each surface, there is thus a maximum wavelength of light that can produce a photoelectron.

Table 1 shows the measured work functions, Φ, for clean polycrystalline surfaces of some metallic elements which have low work functions, as well as the corresponding maximum wavelengths, λ_{max}, for the ejection of a photoelectron. Note that the longest wavelengths quoted are in the green region of the spectrum and the rest range to the violet end. Although another half dozen elements have work functions of 3.10 eV or less and can emit photoelectrons under visible light, most elements have higher to much higher work functions and can only be excited to electron emission by UV light.

Element	Φ (eV)	λ_{max} (nm)
Cs	2.14	580
K	2.30	540
Eu	2.50	496
Na	2.75	451
Ca	2.87	432
Ce	2.90	428
Gd	3.10	400

Table 1

For practical photocathodes, mixtures of elements are often used. The mixtures create a different surface structure that can have a lower work function than either component alone, extending the sensitivity towards the red end of the spectrum. The phototube used in this apparatus contains such a mixed cathode—Cs/Sb (work function of pure Sb: 4.55eV). *Figure 3* shows the spectral sensitivity curve of the phototube included in this apparatus. The photocurrent for constant illumination (in arbitrary units) is plotted against the wavelength of light used. It can be seen that the curve is extended into the red region, although with sharply reduced sensitivity.

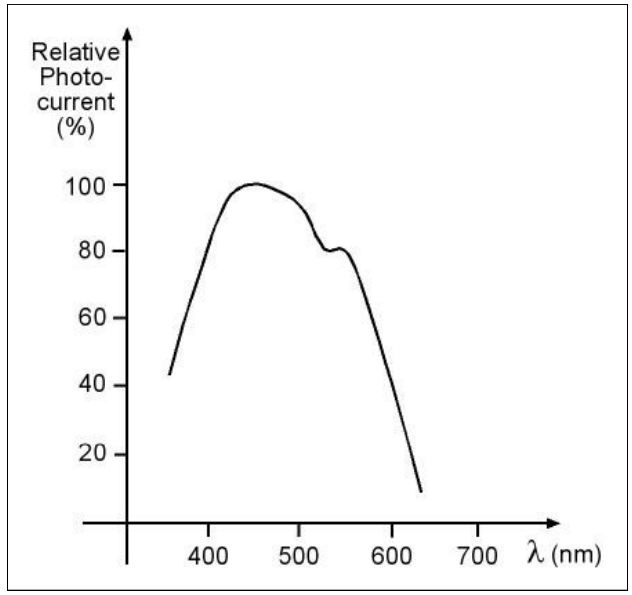

Figure 3

What happens to the ejected electrons? Unless an extraction voltage is applied to remove them from the vicinity of the emitting cathode, they form a "space charge" - a cloud of electrons - above the metal surface. The photoelectrons ejected into the space charge have a positive kinetic energy, and some of them reach the anode, even in the absence of an externally imposed electric field. So there is a small photocurrent with no applied voltage. As the space charge builds up, mutual repulsion spreads it out and also some electrons return to the cathode. The negative net charge increases the barrier to emission until a dynamic equilibrium is reached. Applying an electric field by imposing a positive voltage on a nearby anode has the effect of sloping the vacuum energy line in *Figure 2* "downhill" - see *Figure 4* - so that more electrons can trade potential energy for kinetic energy and move to the anode. As the voltage is increased, the flow of electrons out of the space charge rises until electrons are being extracted as fast as they are emitted and the space charge collapses. The current flow then increases more slowly. The tube is said to be saturated. The resulting photocurrent vs. extraction voltage curve has the form shown in *Figure 5*. The lowest voltage at which this effect can be observed is called the saturation voltage. It is a function of the intensity of the illumination The apparatus allows these photocurrent vs. extraction voltage relationships to be investigated.

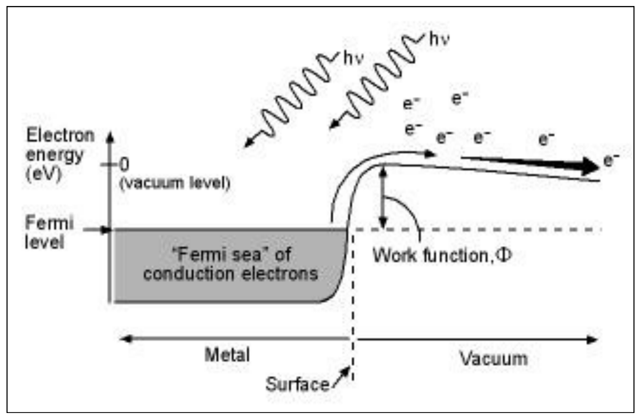

Figure 4

It may be expected that the rate of electron ejection will vary directly with the rate of photon arrival, that is, with the intensity of the illumination. This is indicated by the upper curve in Figure 5, showing the effect of increased cathode illumination. The apparatus allows this relationship to be verified by using a constant current light source to give a stable light output, than varying the light source's distance from the phototube and using the inverse square law to obtain a known illumination variation to compare with the measured photocurrents.

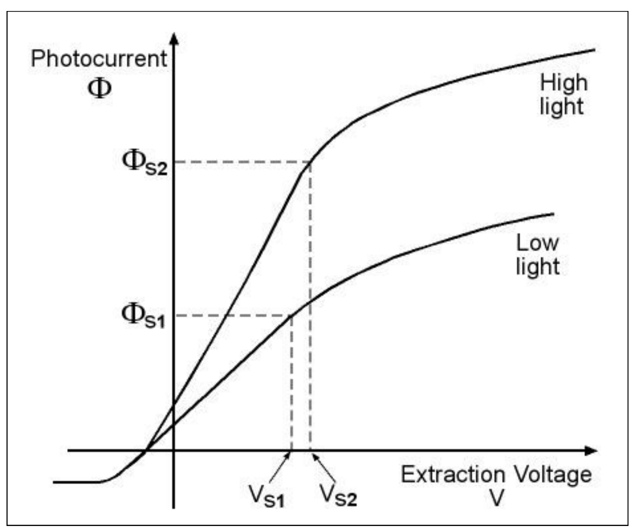

Figure 5

. Operation

5.1 The Phototube

- The GD-51 mixed metal cathode phototube supplied is a diode structure in an envelope with a 7-pin base (see *Figure 6*) A metal shield around the inside of the envelope admits light only through a window in the front. The cathode is on the inside surface of the shield. The anode structure contains a gettering device used during tube manufacture.
- *Figure 6* also shows the tube base viewed from the bottom and identifies the anode and cathode pins.
- The tube socket in the light tight box is also shown in *Figure 6*. It is a 14-pin socket with alternate pin sockets occupied and empty when the tube is in place.
- The apparatus is supplied with the tube in place. Should it be necessary to remove the tube, it should be replaced with the short pin on the tube corresponding to the pin socket facing the lamp (1 in the diagram).

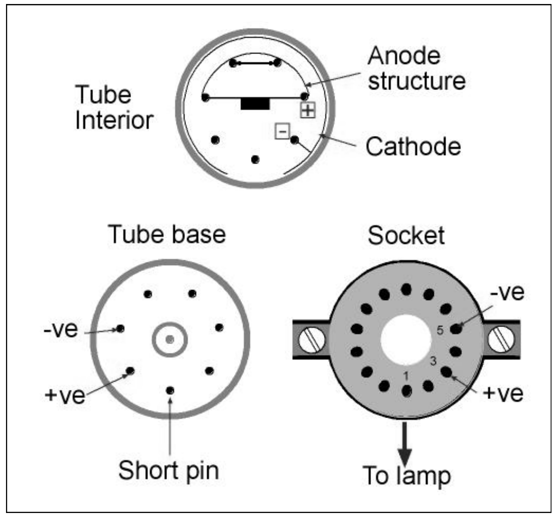

Figure 6

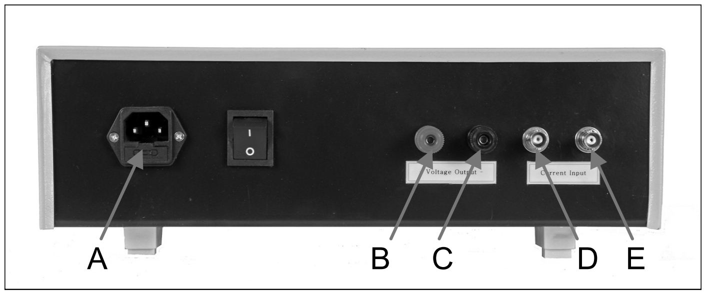

Figure 7

5.2 Setup

- Make the electrical connections between the control unit and the light tight box: *Figure 7* shows the rear of the control unit *Figure 8* shows the end of the light tight box. *Note: the results depend sensitively on the stability of the lamp current and the amplifier. Make sure that the connections are correctly polarized and firmly connected.*
  - Connect the lamp supply. Using the supplied cables with a banana plug and a spade lug, connect the jacks marked B in *Figures 7 & 8* (red) Similarly connect the jacks marked C (black).
  - Connect the phototube signal to the control unit. Using the supplied cables with the BNC connectors and the banana plugs, connect the jacks marked D in *Figures 7 & 8* (red). Similarly connect the jacks marked E (black).
- With the power switch on the off position, connect the supplied power cable to the IEC connector (A in *Figure 7*) and then to a 110VAC outlet.
- Open the light tight box and check that the phototube is properly seated in its socket. Close the light tight box as soon as you have checked.

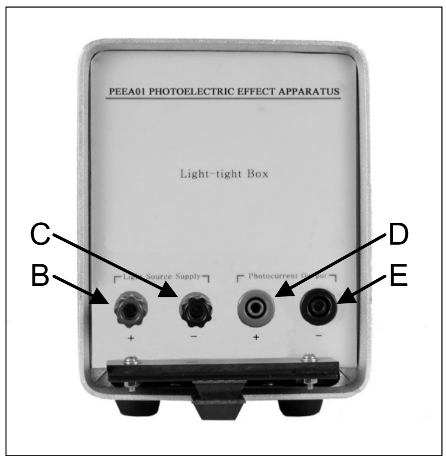

Figure 8

- Set the lamp current potentiometer (7, *Figure 1*) to its minimum value and the extraction voltage potentiometer (9, *Figure 1*) to the approximate center of its range.
- Select the 20μA range for the photocurrent display (12, *Figure 1*).
- Pull out the lamp slide (6, *Figure 1*) until the 10 cm mark is visible at the end of the light tight box.
- Turn on the control unit at the switch and adjust the extraction voltage potentiometer to read “00.0” volts. The apparatus is ready for measurements.

5.3 Calibrating the Slide

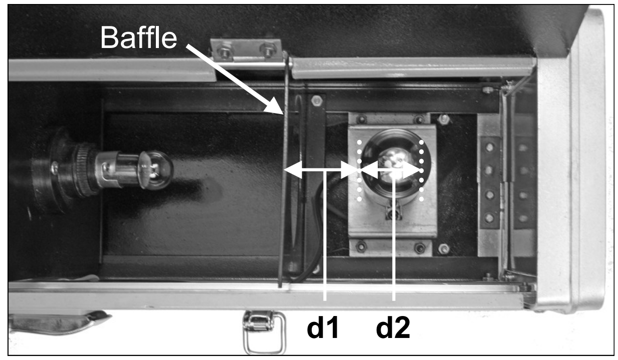

Figure 9

- One investigation requires the distance r between the lamp filament and the tube's photocathode to be measured. The scale on the slide (6, *Figure 1*) is used for this purpose.
- Because of the geometry of the phototube and manufacturing tolerances in the socket bracket and the lamp, the position indicated on the slide scale differs from the distance r by a constant amount, and a correction is required.
- To correct for manufacturing tolerances, proceed as follows:
  - Open the light tight box. There is a fixed baffle in front of the phototube to eliminate unwanted reflections from the inside walls of the light tight box (see *Figure 9*). Move the slide out until the lamp is well clear of the baffle.
  - Use a short metric ruler to measure the distance d1 between the front of the phototube and the center of the baffle.
  - Turn on the control unit and adjust the lamp current to its minimum value. The lamp filament will glow dimly. Move the slide in until the filament is exactly in the center of the baffle and read the position d indicated on the slide scale. The tolerance correction is the difference between d and d1 (usually a small positive addition to d).
  - Close the light tight box as soon as these measurements are finished.
- The illuminated cathode area is a partial cylinder inside the rear part of the phototube. Its effective average distance from the front surface of the tube, d2, is approximately 25 mm. This quantity should also be added to each slide scale reading to obtain an accurate value of r.

5.4 Measurements

5.4.1 Measuring the Characteristic Curves of the Phototube.

- The photocurrent generated by the tube is measured as a function of the applied voltage for several different levels of illumination, characterized by the lamp current.
- Phototubes frequently exhibit a "dark current" - a current flow in the absence of illumination. Such currents arise from a variety of sources, but not from photoemission, so any observable dark current should be subtracted from the measured currents to give an accurate measure of the true photocurrent. The GD-51 phototube used in this apparatus has a very small dark current at all applied voltages, too small to be detected by the photocurrent amplifier, so no dark current adjustments are needed.
- Adjust the slide position so that the filament-cathode distance r is 20 cm.
- Turn on the control unit and set the lamp current to 400mA
- Select the 20μA range of the photocurrent amplifier.
- Starting at 0.0V applied voltage, measure and record the photocurrent as the applied voltage is increased to its maximum value of 23.8V. It is suggested to use steps of 0.1V initially, increasing the steps progressively to 0.5V, 1.0V, and 2.5V as saturation sets in and the photocurrent increases more slowly.
- Graph the resulting current-voltage relationship and identify the space charge and saturation regions as well as the saturation voltage V_s described in Section 4.
- Repeat the procedure for higher lamp currents at intervals of 50mA up to 600mA.
- Compare your estimates of V_s at the various lamp current levels to verify its increase with increasing illumination.

5.4.2 Measuring the Suppression Voltage of the Phototube.

- It was pointed out in Section 4 that there is a small photocurrent at zero imposed voltage due to the kinetic energy of the emitted electrons. The suppression voltage of the tube is that imposed negative voltage required to reduce the photocurrent to zero. The photocurrent amplifier and display can indicate a current greater than 5nA, so the apparatus can determine a suppression voltage to this level. (*Note: This is not sufficient for an accurate determination of Planck's constant using color filters.*)

- Set the filament-cathode distance to 20 cm and the lamp current to 400mA.
- Set the voltage to 00.0 V and record the photocurrent.
- Reduce the voltage in steps of 0.1V, recording the photocurrent each time, until the photocurrent is shown as zero.
- Repeat the process for higher lamp currents, increasing the current in steps of 50mA to 600mA.
- Compare the suppression voltages found for the various illumination levels.

5.4.3 Measuring the Photocurrent Variation with Lamp Distance.

- Since the light flux produced by the lamp is not a linear function of the lamp current, the investigation of the variation of the photocurrent with the intensity of illumination of the photocathode is accomplished by using a fixed lamp current and varying the filament-photocathode distance, then using the Inverse Square Law to plot the form of the photocurrent as a function of the intensity of illumination.
- To ensure that all the photoelectrons produced reach the anode and contribute to the measured photocurrent, the tube is operated in the far saturation region. Set the applied voltage to its maximum value (23.8V)
- Set the lamp current to 500mA
- Adjust the slide so that the filament-cathode distance r is 10 cm (*Remember to take account of the corrections described in Section 5.1*) and record the photocurrent.
- Increase the filament-cathode distance r in increments of 5 cm to 40 cm, recording the photocurrent each time.
- Calculate the values of $1/r^2$ and draw the graph of photocurrent vs. $1/r^2$.
- Optionally, repeat the procedure for other values of the lamp current between 400 mA and 600 mA.

6. Discussion

6.1 The Characteristic Curve

- A typical characteristic curve is shown in *Figure 10*. It is clear from the form of the curve that the saturation voltage is not well defined. However, a space charge-dominated region and a saturation-dominated region can be clearly identified, with the transition occurring at approximately 5V extraction voltage in the example shown. This can be taken as the saturation voltage.
- Examination of the full series of characteristic curves will show that the transition between the space charge and saturation regions shifts to higher voltages with increasing illumination, as noted in Section 4. Since increased illumination results in a faster rate of emission of electrons, replenishing losses to the space charge faster, it is not surprising that a higher extraction voltage is needed to deplete the space charge and produce a saturation condition.

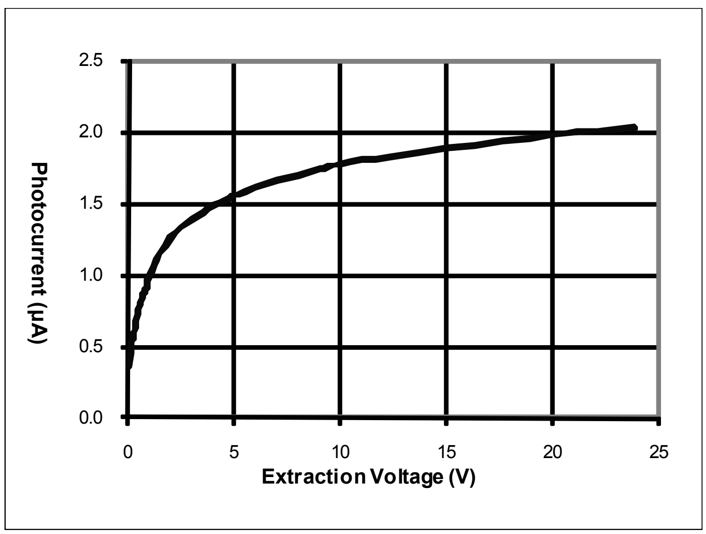

Figure 10

6.2 The Suppression Voltage

- The suppression voltage for a phototube illuminated by a broad spectrum lamp is also not well defined. As the temperature of the lamp filament is increased, more light of shorter wavelength is included in the mix of photons emitted and a larger number of electrons with greater kinetic energy will be released. The measured suppression voltage will therefore move to more negative values. This effect should be observable in this apparatus with careful measurement.
- The actual values obtained for the suppression voltage (a few tenths of a volt) are largely determined by the sensitivity of the photocurrent measuring arrangement. In this apparatus, a current change of about 5nA can be detected by a change of one unit in the last digit displayed. This therefore represents the lower limit for determining when the photocurrent becomes "zero." A more sensitive detection system would find a more negative suppression voltage.
- The conclusion can be drawn that the kinetic energy spectrum of the emitted electrons reaches at least to 0.2eV.

6.3 Variation of the Photocurrent with Illumination

- The photocurrent is expected to vary linearly with the intensity of the illumination. *Figure 11* is a typical plot of the measured photocurrent against the inverse square of the distance between the lamp filament and the photocathode. It shows an approximately linear relationship but with clearly visible deviations.
- There are two main sources of error in the measurements:
  - The assumption that the intensity of illumination varies as $1/r^2$ is based on an assumed point source of light. However, the lamp filament is actually an extended source. At small distances, the error caused by this is much larger than at small distances, where it is less significant.
  - The semi-cylindrical photocathode is illuminated through a 22mm wide window in the front of the metal shield inside the tube. As the distance of the filament from the window increases, the included angle of the light rays admitted by the window decreases, so decreasing the illuminated area of the cathode. Since the assumption that the illumination varies as $1/r^2$ also depends on a constant cathode area, this is a second source of error.

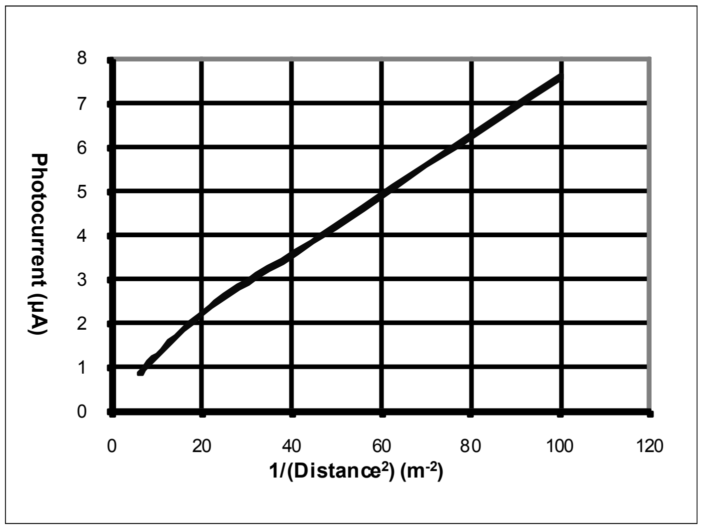

Figure 11

7. Maintenance and Troubleshooting

7.1 Maintenance

- The Photoelectric Effect Apparatus needs no special maintenance except for the possible replacement of a burned-out fuse or lamp bulb.
- The fuse is located on the lower part of the IEC power cord socket (see *Figure 7*). Unplug the apparatus from the 110VAC outlet before removing the fuse tray with the tip of a screwdriver. Replace the fuse with a 5 x 20 mm miniature fuse rated at 250V/1.5A. DO NOT USE A HIGHER-RATED FUSE to avoid damage to the apparatus.
- To prolong the life of the phototube, always keep the light tight box closed, except for brief inspections of the interior.
- Store the apparatus in a cool, dry place away from sunlight.

7.2 Troubleshooting

- The apparatus is robust and the electronics are very stable, so no trouble should be encountered in normal operation, provided that attention is paid to correct connection of the light-tight box to the control unit.
- The lamp current is stabilized to less than 0.5 mA. This is necessary because of the high sensitivity of the photoemission to the illumination intensity and its rapid reaction to changes. To maintain this stability, it is necessary to have very good contact at all the connection points in the circuit so as to avoid random load changes due to unreliable contact resistances. If flickering of the digits of the lamp current display is observed, check the following connections:
    - The current input spade lug connectors on the light-tight box should be clean, properly seated and tight;
    - The current output plugs/sockets on the control unit rear should be clean and properly and firmly mated;
    - The bayonet connection of the lamp can become unreliable after prolonged operation due to oxidation and creep of the soft metal contacts at the warm operating temperatures. Remove the lamp, clean the contacts and replace the lamp in its socket.
- The photocurrent amplifier and display are sensitive to current changes of 5nA. To retain reasonable stability at this sensitivity, all the connection points in the circuit should be reliable. Some small variation of the photocurrent over time is normal, especially at lower extraction voltages. However, last digit flicker of more than one unit in the display indicates a poor connection. Check both ends of the shielded photocurrent connecting cables for dirt or loose connections.
- Check that the tube is correctly seated in its socket (see *Figure 6*, Section 5.1)
- Pay particular attention to the correct polarity of the photocurrent connections to avoid misleading readouts.

8. Accessories and Replacement Parts

The Photoelectric Effect Apparatus comes with all necessary accessories. For replacement of lost or broken parts, contact your United Scientific Supplies distributor.