

Photoelectric Effect

The ejection of electrons from a surface by the action of light striking that surface is called the *photoelectric effect*. In this experiment, as you investigate the photoelectric effect, you will examine some of the fundamental particle-like properties of electromagnetic radiation (photons) and determine one of the fundamental constants of physics: Planck's constant h .

Theory

In 1905 Albert Einstein called into question the classical theory of light, proposed a new theory, and cited the photoelectric effect as one application that could test which theory was correct. Max Planck originally restricted his concept of energy quantization to the radiating electron in the walls of a blackbody cavity. His postulate stated that any physical entity undergoing simple harmonic motion possesses only total energies that satisfy the quantization condition:

$$E = n(h\nu) \quad n = 1, 2, 3, \dots \quad (1)$$

where ν is the frequency of oscillation and h is a universal constant (Planck's constant):

$$h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s}. \quad (2)$$

Planck believed however that electromagnetic energy, once radiated, spreads through space like water waves spread through water. Einstein proposed instead that radiant energy is quantized into concentrated bundles which later came to be called *photons*. He argued that the well-known optical experiments on interference and diffraction of electromagnetic radiation involve very large number of photons, and therefore yield results which are averages of the behaviours of individual photons.

Einstein focused his attention on the particle-like way in which the electromagnetic radiation appeared to be emitted and absorbed. Planck showed that the energy of an electromagnetic wave of frequency ν in a radiant source can only be $n h \nu$, where n is an integer. From this Einstein reasoned that in the process of going from a state with energy $n h \nu$ to a state with energy $(n - 1) h \nu$, the source would emit a discrete burst of electromagnetic energy with energy content $h \nu$.

Einstein assumed that

- the photon is initially localized in a small volume of space, and *it remains localized as it moves away from the source with velocity c*
- a photon carries an energy $E = h \nu$

- in the photoelectric process, a photon is *completely* absorbed by a *single* electron.

When the electron is emitted from the surface of the metal, its kinetic energy will be

$$K = h\nu - W \quad (3)$$

where $h\nu$ is the energy of the absorbed incident photon and W is the work required to remove an electron bound to the metal. Some electrons are bound more tightly than others, while some lose energy in collisions on the way out. For a given photon energy, the emitted electron will have its maximum possible kinetic energy K_{max} if

- it does not lose energy on the way out
- it is bound with the least binding energy W_0 . In other words

$$K_{max} = h\nu - W_0 \quad (4)$$

where W_0 is a characteristic energy of the metal, and is called the *work function*. W_0 is the minimum energy needed by an electron to pass through the metal surface and escape the attractive forces that normally bind the electron to the metal.

The classical wave model predicted that *as the intensity of incident light is increased, the amplitude and thus the energy of the electromagnetic wave would increase*. This would then cause more energetic photoelectrons to be emitted. Einstein's quantum model, however, predicted that light with a *higher frequency* would produce higher energy photoelectrons, independent of its intensity. On the other hand, increased intensity would only increase the *number* of electrons emitted (or photoelectric current).

In 1914 Robert Millikan (the same physicist who measured the charge of the electron) proved experimentally that indeed the kinetic energies of the photoelectrons were dependent on the frequency of the incident radiation. In addition he showed that the photoelectric current, or number of electrons emitted per unit time, was dependent on the intensity, as predicted by Einstein's formula.

Experiment:

Apparatus:

- Mercury vapour light source
- digital voltmeter (DVM)
- h/e apparatus (PASCO AP-9368)
- coupling bar assembly
- lens/grating assembly
- yellow and green filters
- variable transmission filter

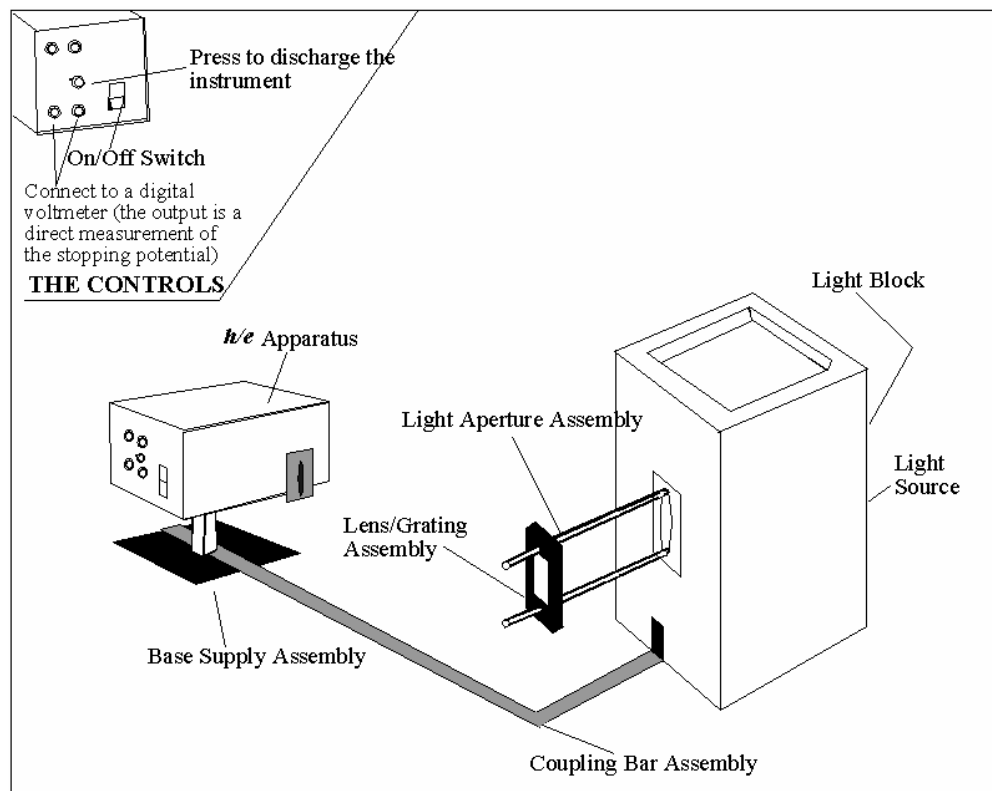


Figure 1. Equipment setup using a mercury vapor light source and the h/e apparatus.

Suppose that a light photon with energy $h\nu$ is incident upon an electron in the cathode of a vacuum tube. The electron uses at least W_0 of its energy to escape the cathode, leaving it with at most a maximum kinetic energy of K_{max} . Normally the emitted electrons reach the anode of the tube, and can be measured as a photoelectric current. However, by applying a reverse potential V between the anode and the cathode, the photoelectric current can be stopped. K_{max} can be determined by measuring the minimum reverse potential needed to stop the photoelectrons and reduce the photoelectric current to zero. This potential is called *the stopping potential* V_0 . In this experiment, the stopping potential V_0 is measured directly, rather than by monitoring the photoelectric current.

Relating kinetic energy to stopping potential gives the equation

$$K_{max} = eV_0 \quad (5)$$

Combining Eqs. 4 and 5 gives

$$V_0 = (h/e)\nu - (W_0/e) \quad (6)$$

Thus Einstein's theory predicts a linear relationship between the stopping potential V_0 and the frequency ν of the incident radiation. If we plot V_0 vs. ν we obtain a straight line whose slope, together with the accepted value for e yields Planck's constant h . $e = 1.602 \times 10^{-19}$ C

Theory of Operation

In experiments with the h/e apparatus, monochromatic light falls on the cathode plate of a vacuum photodiode tube that has a low work function, W_0 . Photoelectrons ejected from the cathode collect on the anode.

The photodiode tube and its associated electronics have a small capacitance which becomes charged by the photoelectric current. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero, and the anode-to-cathode voltage stabilizes. This final voltage between the anode and the cathode is therefore the stopping potential of the photoelectrons. To let you measure the stopping potential, the anode is connected to a built-in amplifier with an ultra-high input impedance ($\approx 10^{12}\Omega$), and the output from this amplifier is connected to the output jacks on the front panel of the apparatus. This high impedance, unity gain [$(V_{out}/V_{in})=1$] amplifier has low enough output impedance that it lets you measure the stopping potential with a digital voltmeter.

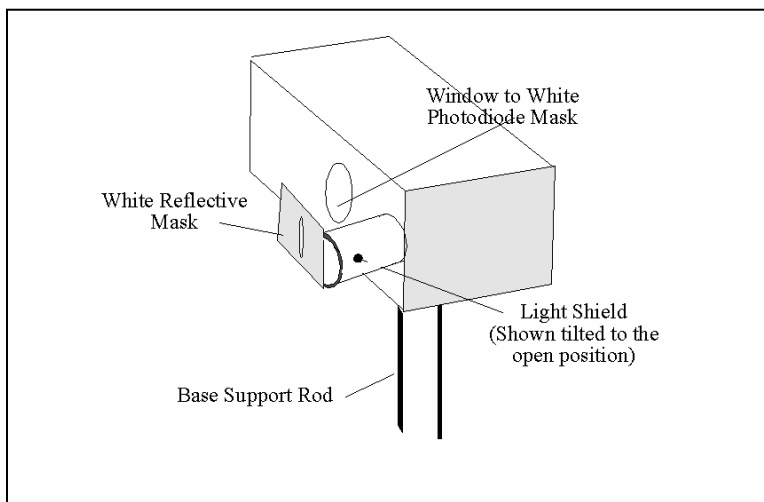


Figure 2. The h/e apparatus light shield

Experimental Setup

1. Set the h/e apparatus directly in front of the Mercury Vapour Light source. By sliding the Lens/Grating assembly back and forth on its support rods, focus the light onto the white reflective mask of the h/e apparatus (See Figs. 1 and 2) **Note: The grating is blazed to produce the brightest spectrum on one side only.**
2. Roll the light shield of the apparatus out of the way to reveal the white photodiode mask inside (Fig. 2). Rotate the h/e apparatus until the image of the aperture is centered on the window in the photodiode mask. Then tighten the thumbscrew on the base support rod to hold the apparatus in place.

3. As in step 1, slide the *lens/grating* assembly back and forth on its support rods, until you achieve the sharpest possible image of the aperture on the window in the photodiode mask. Tighten the thumbscrew on the *lens/grating assembly* and replace the light shield.
4. Turn the power switch ON. Rotate the *h/e* apparatus about the pin of the *coupling bar assembly* until one of the coloured maxima in the first order shines directly on the slot in the *white reflective mask*. Rotate the *h/e* apparatus on its support base so that the same spectral maximum that falls on the opening in the *white reflective mask* also falls on the window in the photodiode mask.
5. Press the ZERO button on the side panel of the *h/e* apparatus (near the ON/OFF switch - see Fig. 1) to discharge any accumulated potential in the unit's electronics. This will assure that the apparatus records only the potential of the light that you are measuring.
6. Read the output voltage on your digital voltmeter. It is a direct measurement of the stopping potential for the photoelectrons.

IMPORTANT: When making measurements it is important that only one colour falls on the photodiode window. There must be no overlap from adjacent spectral maxima.

Using the filters:

Your experiment includes three filters: one Green, and one Yellow, plus a Variable Transmission Filter. The filter frames have magnetic strips and mount to the outside of the White Reflective Mask of the *h/e* apparatus.

Use the green and the yellow filters when you're using the green and yellow spectral lines. These filters limit higher frequencies of light from entering the *h/e* apparatus. This prevents ambient room light from affecting your results. The filters also block the higher frequency ultraviolet light from the higher order spectra which may overlap with lower orders of yellow and green.

The *variable transmission filter* consists of computer-generated patterns of dots and lines that vary the intensity (not the frequency) of the incident light. The relative transmission percentages are 100%, 80%, 60%, 40%, and 20%.

Procedure

1. Adjust the *h/e* apparatus so that only one of the yellow coloured bands fall upon the opening of the mask of the photodiode. Place the yellow coloured filter over the *white reflective mask* on the *h/e* apparatus.

Colour	Approximate Wavelength (nm)
Yellow	578
Green	546
Blue	436

Violet #1	405
Violet #2	365

Table 1: Prominent lines in the mercury spectrum.

- Place the *variable transmission filter* in front of the *white reflective mask* (and over the coloured filter, if one is used) so that the light passes through the section marked 100% and reaches the photodiode. Record the DVM voltage reading. Press the instrument discharge button, then release it.
- Move the *variable transmission filter* so that the next section is directly in front of the incoming light. Record the new DVM reading. Press the instrument discharge button, then release it.
- Repeat the last step until you have tested all five sections of the variable transmission filter.
- You can easily see five colours in the mercury light spectrum. Repeat the process for each colour. Be sure to use the green filter when measuring the green spectrum. The wavelengths of these five colours are given in Table 1.

Analysis

- Describe the effect that passing different amounts of the same coloured light through the *variable transmission filter* (i.e. different intensities) has on the stopping potential and thus the maximum energy of the photoelectrons.
- Describe the effect that different colours of light had on the stopping potential and thus the maximum energy of the photoelectrons.
- Defend whether this experiment supports a wave or a quantum model of light based on your laboratory results. Note: While the impedance of the zero gain amplifier in the h/e apparatus is very high ($\approx 10^{12}\Omega$), it is not infinite and some charge leaks off. This leakage becomes more apparent for low intensities of electromagnetic radiation and then a smaller number of photoelectrons are emitted. For this reason there is a slight drop in the measured stopping potential as the light intensity is decreased.
- Plot a graph of the *stopping potential vs the wavelength*, and a graph of the *stopping potential vs the frequency*.
- If either graph is a straight line, determine the slope and y-intercept. Interpret the results in terms of the h/e ratio and the W_0/e ratio. Calculate h and W_0 .