Photoelectric Effect

Object
To verify that light is composed of photons, and determine the work function of the cathode of the phototube.

References


- Eisberg and Resnick. *Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles*


Apparatus

RCA 934 phototube, two Fluke 37 multimeters, Hewlett-Packard 6235A Triple Output Power Supply, Halogen Table Lamp, set of light filters.
I. Introduction

Historical Note:

Albert Einstein was awarded the 1921 Nobel Prize in physics: "For his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect." According to Pais (see references) Einstein was not specifically cited for his work on relativity because either the Nobel Academy did not believe the experimental results clearly agreed with theory or the Academy lacked competent members who understood the theory.

Theory:

The theory of the photoelectric effect is that photons of energy, $h\nu$, can free electrons from the surface of a material if the photon energy is greater than the work function, $W$. The work function is the energy that binds the electron to the surface. This energy depends upon the material composition. When an electron in a material absorbs a photon it can get enough energy to escape out of the volume of a substance. The ejection of the electron is called the photoelectric effect. The photoelectric effect predicts that the energy of the free electron, $E$, is directly proportional to the photon's frequency.

$$E = h\nu - W$$

In this equation $h$ is the Plank constant, $\nu$ is the frequency of the light, and $W$ is the work function which is equal to the photon energy required in order to extract an electron from a substance with zero final kinetic energy. The work function is constant for a given substance. The origin of the work function is that each electron is initially trapped in the electrostatic potential well defined by the aggregate of the atoms of the substance, and energy must be provided to free it.

Note that the kinetic energy of an electron is linearly proportional to the photon energy. The latter should exceed the work function to cause photoelectron production.

Electron kinetic energy can be measured by applying a stopping potential between the cathode and the anode of a phototube. The minimal value of the stopping potential resulting in no current (photoelectrons are fully stopped on the way to the anode) is equal to electron kinetic energy measured in eV's.

The objective of this experiment is to examine the above theory by finding the work function and verifying that the electron energy is linearly proportional to the photon frequency.

II. Experimental arrangement

The circuit for the photoelectric experiment centers around an RCA 934 phototube. The curved cathode of the phototube emits free electrons when photons strike the surface.

When the photons impart enough energy, $h\nu$, to overcome the work function, $W$, of the cathode material, a free electron (of negative charge $q$) leaves the surface. At the center of the cathode's radius of curvature is an anode that will collect the electrons emitted by the cathode.
The theory of the circuit is to determine the electron energy by applying a reverse voltage between the anode and cathode which will stop the electrons from getting to the anode. The reverse voltage that stops the electrons from making it to the anode is the "stopping potential" which is a measure of the free electron's energy, $E$.

$$V_{sp} = \frac{E}{q} = \frac{(h\nu - W)}{q}$$

The circuit consists of two parts. On the left is a voltmeter reading the Stopping Potential, the voltage applied across the cathode to anode which will stop the free electrons from making the jump from the cathode to anode. This voltage, $V_{sp}$, measures the free electron energy. The potentiometer labeled Stopping Voltage controls the applied voltage. The range is adjustable from 0 to 3 volts. Nominally, the voltage is less than 1.5 V down to 0.

The stopping voltage is read from $V_{sp}$ but whether free electrons have been fully stopped is measured by the right-hand side amplifier circuit. When $V_{offset}$ is 0 V, the voltage $V_{sp}$ is stopping the free electrons. Because there are offsets in op-amps, the circuit must be nulled (zeroed). The second potentiometer, Offset (Balance) Voltage, is adjusted to 0 V when no light strikes the cathode. That is, $V_{offset}$ should read 0 V when no light is striking the cathode regardless of the setting of $V_{sp}$.

The light source is a high intensity halogen lamp which consists of an incandescent filament surrounded by argon gas that emits additional light at the short wavelengths. The photon energies are screened by using optical interference filters placed in the "well" at the instrument top. A cover is used to keep dust out of the instrument. Each filter has an identification number which is used to find the approximate wavelength from the storage box. The precise wavelengths are obtained from the filter calibration curves found in a binder that should be kept on the experiment table.

On the experimental apparatus the following labels are used:

**OUTPUTS:**

Stopping Potential Output: a BNC connection running to a voltmeter

Balance Output: a BNC connection running to a voltmeter.
ADJUSTMENTS:

Stopping Potential Adjustment: potentiometer controlling the applied $V_{sp}$.

Zero Adjustment: potentiometer controlling the offset $V_{offset}$.

POWER REQUIREMENTS:

One SRS power supply is adjusted for $+3V$, $+18V$, and $-18V$. Note that one ground connection between the power supply and apparatus is sufficient. The second ground connection is redundant. A single supply is given that produces all these voltages. Check everything before running the experiment.

LIGHT SOURCE:

The tungsten-halogen lamp should be placed 4 inches above the top of the instrument where the entrance aperture is. A filter is placed on the aperture.

The filters must be stored in their individual boxes and not left unprotected on the table. They break easily if dropped.

PHOTOTUBE:

The RCA 934 phototube uses a cathode of Cesium-Antimony. Reference (Mielke) claims that the work function is $-1.7 v$. This should be verified by your experiment.

III. Experimental procedure

1. It's a good idea to set balance output to zero, before each measurement, while the aperture is covered by the lid. After the measurement verify that the balance output is still zero. If it isn't you must make a correction for the difference.

2. For each filter find the electron kinetic energy by adjusting the stopping potential so that the phototube current is zero. Record the stopping potential and the wavelength for that filter. Also record the balance reading before and after the measurement.

IV. Analysis

Plot your data (electron energy vs. photon energy) using any linear fit program. The photon energy can be obtained from the wavelength using the relation $E_{photon} = \frac{hc}{\lambda}$. By the way, the value of $hc$ in eVnm is 1240.

The best fit to perform is what Kaleidograph calls a weighted fit. This is a true $C^2$ minimization. To use it you must determine the uncertainties in your experimental measurements. You could do this in two ways. One is to observe the variation of the meter readings over a few seconds and write this down as an uncertainty in your reading. The other is to make several measurements and call the uncertainty the standard deviation of these measurements.
Determine the work function.

V. Discussion

1. Does electron kinetic energy depend on the light intensity?
2. What is the range (in eV's) of the visible light photon energy?
3. Is the photoelectric effect possible for free electrons?