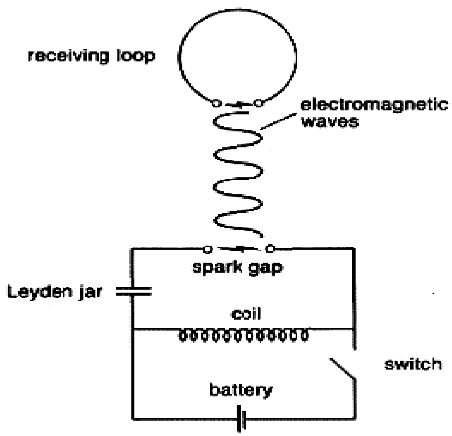
Photoelectric Effect

<table>
<tr><th>Screen (Video)</th><th>Text/Audio</th><th>Remarks/Action</th></tr>
<tr><td rowspan="2">

Hertz Expt.</td><td>History:
The photoelectric effect discovered accidentally by Hertz, in 1887 and explained by Einstein in 1905. During the experiments, Hertz produced electromagnetic waves. He used two metal knobs, for detecting these waves. However, instead of detecting these waves, a spark induced between two metal knobs. In addition, he noted that when the knobs illuminated with ultraviolet light, the sparks were much brighter. Thus, charge particles emitted, when the electromagnetic wave incident is on metal plate. Later on, this effect called by the name ‘photoelectric effect’.</td><td rowspan="2"></td></tr>
<tr><td>It has been found experimentally that when light shines on a metal surface, the surface emits electrons, called photoelectrons.</td></tr>
<tr><td></td><td>In 1888, Hallwachs discovered that the negatively charged metal surface loses its charge when irradiated with ultraviolet light, but the light has no effect on a positively charged metal surface. It was also observed that when ultraviolet light was incident on a negatively charged zinc plate, it loses its charge rapidly, becomes neutral and then it becomes positively charged.</td><td></td></tr>
<tr><td></td><td>In 1897, J. J. Thomson made discovery of electron. He observed negative charged particles emitted by zinc plate in 1898. Thomson studied these particles vigorously and concluded that they were fundamental building blocks of material and he named them as electrons.</td><td></td></tr>
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Experimental study:

This apparatus is use to study the photoelectric effect. Two metal plates are mounting in highly evacuated glass tube. A photosensitive material is place on one of the plate and other plate is use to collect the electrons. Variable supply is connecting between these two plates and current meter is connecting in series to measure the current through the circuit.

In this experiment, three knobs are used:

- First knob is used to vary the intensity of incident light on photosensitive material
- second knob is used to vary the wavelength of incident light and
- third knob is used to vary the voltage between two plates

Let us perform the experiment of photoelectric effect.
Experiment is loading…
Please wait

Two windows are displayed on the screen.

1. Photoelectric experiment (white window) and
2. Instructions (black window behind the experiment window)

Select blue strip of the experiment window and move it to the right-hand corner on the screen.
If you click on instruction window, it will come up.
To adjust the position of this window select blue strip by mouse and move it to the left-hand corner on the screen.

Press Next button.

If you click outside of these windows and if both these windows are minimize then icon will display at the bottom on the screen on the toolbar.
To re-open these windows select icon of each window and click.
For demo, click outside of these windows and if it minimized, then click icon of these windows which will displayed at bottom on the screen on the toolbar *by the name* 'Macromedia Flash Player' *and* 'The Photoelectric Effect'.

Experiment 1:
Photoelectric current verses light intensity.

In this experiment, vary the light intensity knob shown near the lamp and observe the result.
To vary the intensity of incident light, select intensity knob by mouse and move it towards right-hand side.

Observation:

1. Light intensity increases if knob moves to the **left/right** hand side.
2. Electrons emitted due to incident of light on photoelectric material, called ………..
3. By increasing the intensity of incident light, number of emitted photoelectrons **increases/decreases.**
4. In actual experiment, are you able to see the emitted photoelectrons? **YES/NO.**
5. In actual experiment, how do you guess the emitted photoelectrons?
6. In routine life, how is it possible to vary the intensity of electric bulb?

Conclusion:
In this experiment, number of emitted photoelectrons noted by current through the circuit is directly proportional to the intensity of incident light.

What is the relation between number of emitted photoelectrons and current flowing through the circuit?
1 A = …… electrons flow per second.
Click here to find answer
Answer: 1 A current means 1 C charge flows per sec.
Charge on electron is 1.6×10^{-19} C.
Therefore $1/ 1.6 \times 10^{-19}$ = $\mathbf{6.24 \times 10^{18}}$ electrons required to make up 1C charge.
Or
1 A current means $\mathbf{6.24 \times 10^{18}}$ electrons flow per unit second.

While performing the experiment, note the wavelength of incident light, shown below the intensity knob (by default it is 400 nm). Find the corresponding frequency by using equation $c = \upsilon\lambda$. Note the photoelectric material used in the experiment (by default it is *Sodium*), which displayed at the right hand side. Increase the light intensity of incident rays by the step of 10% and note the corresponding current.
Plot the graph of current verses light intensity in your notebook. For plotting the graph, independent quantity **current/light intensity** be plotted on **X/Y** axis.
Answer: *light intensity* is independent quantity so plot it on X-axis.
To verify the plotted graph with simulated graph select *'Current verses Light intensity'* option shown below the heading '*Graphs*' in the experiment window. After selecting graph option, repeat the experiment for all given photosensitive material. You may adjust the scale of simulated graph using '+/ – lens knob', given near the graph.
Conclusion: In the photoelectric experiment by increasing intensity of incident light on photoelectric material, current through the circuit **increases/decreases**.

Experiment 2:

Photoelectric current verses light intensity at different wavelength.

This experiment is similar to above experiment. Note current verses light intensity at different wavelengths.

To perform the experiment, steps are as follows:

1. Select wavelength knob given below the light intensity knob. Move it to the left hand side and adjust the wavelength 200 nm i.e. in the UV (Ultraviolet) region.
2. Note the wavelength and find the corresponding frequency by using equation $c = \upsilon\lambda$.
3. Select the graph option: '*Current verses light intensity'* and *'Electron energy verses light frequency'* (if it is not selected).
4. Vary the intensity knob from minimum to maximum by the step of 10% and note corresponding current in your notebook.
5. It is observed that number of photoelectrons increases by increasing intensity of incident light causes increase in the current but the speed of electrons remain constant.
6. You may observe from the graph that photoelectric current is directly proportional to intensity of incident light.
7. By selecting 'Camera' knob given above the lens knob, store this graph on the screen and move it to proper position using blue strip.
8. Increase the wavelength λ by the step of 100 nm and repeat steps 2 to7 five times, so wavelength varies from 200 nm to 600 nm.
9. It is observed that the speed of emitted photoelectrons decreases by decreasing frequency. It is also observed; after certain minimum frequency there is no emission of photoelectrons. This frequency is called as threshold frequency. Click here to adjust the threshold frequency:
10. It is observed from the experiment and the graph for a given photosensitive material:
    i. A certain minimum frequency (threshold frequency υ_0) is required to emit the photoelectron.
    ii. Number of emitted photoelectrons or photoelectric current is directly proportional to the intensity of incident light.
    iii. Though number of photoelectrons increases by increasing the intensity of light but speed of photoelectrons remains the same.
    iv. Speed of photoelectrons as well as photoelectric current increases by increasing frequency. Also it is observed from the graph, kinetic energy (speed) of photoelectrons is directly proportional to the frequency.
11. Select other photosensitive material and repeat all above steps.

Steps to find the threshold frequency:

1. Adjust the intensity to about 50%.
2. Adjust wavelength knob so that current through the circuit becomes just zero. Though current through the circuit shows zero, some time, photoelectrons emits, that is because of limitations of current meter (0.001 A or 1 mA). In that case, select the wavelength-window by mouse and type the appropriate wavelength from the key board so that the emitted photoelectrons just vanish.
3. Now if you decrease the wavelength of incident light by 1 nm you will see that the photoelectrons just start to come out. Note this wavelength and calculate the corresponding frequency. This frequency called as a threshold frequency υ_0 for a given material.
4. Using above steps find threshold frequency of Sodium.
5. Using this experiment threshold frequency υ_0 of Sodium is 539 nm.
6. Select other photoelectric material and repeat the experiment.

Conclusion:

For a given material, certain minimum frequency is required to emit photoelectron called **threshold frequency**.

Observation:

Note the threshold frequency of all given photosensitive material.

Threshold frequency of all given photosensitive material is equal/not equal.

Why threshold frequency is varying with the photosensitive material?

Click here for answer:

Answer:

In photoelectric experiment, here we can vary the wavelength of source, simply by varying the given knob; but in actual experiment how it is possible to vary the wavelength of given source.

Click here for answer:

Answer:

Let us perform the experiment of color vision.
Experiment is loading…
Please wait

Two windows are displayed on the screen.

3. Photoelectric experiment (white window) and
4. Instructions (black window behind the experiment window)

Select blue strip of the experiment window and move it to the right-hand corner on the screen.
If you click on instruction window, it will come up.
To adjust the position of this window select blue strip by mouse and move it to the left-hand corner on the screen.

Press Next button.

Red, green and blue (RGB) monochromatic bulbs are shown with slider.

1. Upper left-hand corner of the experiment window displayed with two options:
    a. RGB bulb
    b. Single bulb

2. Background of RGB bubs is faint blue; indicates experiment is selected.
3. Move the slider of each bulb slowly and observe result.
4. Select single bulb option.
5. White bulb option is selected by default, which is shown at the right-hand upper-corner of the experiment window.
6. Move the slider slowly and observe result.
7. Here slider movement shows variation of filter colour.
8. Thus, by using filter we can change the wavelength of white light.
9. Select monochromatic bulb option (given below the white light option).
10. Observe the result by moving sliders of bulb colour, filter colour and beam view.

Effect on photoelectrons due to variation of potential difference between two plates:

1. For a given photosensitive material, adjust the frequency greater than threshold frequency.
2. Set the intensity of incident beam near about 50%.
3. Select graph options of '*Current verses battery voltage*' and move the voltage knob from minimum to maximum. Display shows the voltage - 8 V at minimum position and +8 V at maximum position. This is the potential on collector plate, w.r.t. photosensitive plate.
4. Observe the result and select the proper choice:
    - Photoelectrons accelerate/de-accelerate if the potential of collector becomes positive with respective to photosensitive plate.
    - Photoelectrons de-accelerate if the potential of collector becomes positive/negative with respective to photosensitive plate called ***retarding potential***. If this potential increases slowly, then de-accelerated electrons just stopped and reversed. This is called ***stopping potential 'V_0'***.
5. Vary the intensity of incident rays.
7. Observe the result and select correct choice:
    - ***Stopping potential 'V_0'*** is dependent/independent on the intensity of incident radiation for a given monochromatic (constant wavelength or frequency) rays.
8. Vary the frequency and find ***stopping potential***. Plot the graph of stopping potential versus frequency. Select correct choice from the result:
    - ***Stopping potential 'V_0'*** increases *linearly/exponentially* by *increasing/decreasing* incident radiation frequency.
9. Select other photoelectric material and repeat above steps to find ***stopping potential***. Select correct choice from the result of slope of the graph of stopping potential versus frequency:
    - For the different material slopes are *same/different*.
    - Slope is equal to '*he'/ 'h/e' / 'e/h' / '1/eh'.*
    - Intersections of graph on frequency axis are *same/different* for the different materials.
    - Intersection on frequency axis represents *stopping potential/threshold frequency* of the material.

Though the photoelectric effect looks very simple, but, if we look more closely at the data, certain points cannot be understood from the electromagnetic theory of light with the ideas of classical physics prevalent at around year 1900.

Steps to perform this experiment are:

A. To find relation between light intensity and photoelectric current at various wavelengths (or frequencies):

1. To start the experiment, select intensity knob by mouse and move it to the right side. When knob is moving corresponding light intensity will be displayed.
2. When light is incident on photosensitive material (like sodium), it emits electrons and current will flow through the circuit. This phenomenon is known as photoelectric effect and the emitted electrons are called photoelectrons.
3. Three options are shown at right side with heading 'Graphs'. Click it to display the graphs.
4. Now vary the light intensity from 0% to 100% and note current through the circuit and observe carefully variations in the graphs.
5. Below the voltage knob, 'Pause' button is given for pause the experiment. When experiment is paused, 'Step' button becomes active to use for step-wise execution. Then use 'Pause' button to replay.
6. To adjust the scale of a graph use magnifier or de-magnifier lens given at right side.
7. Store the graph, using 'camera' button, which is given above the magnifying lens.
8. By default, wavelength of incident light is 400 nm (violet colour).
9. Decrease the wavelength by moving wavelength knob to left side.
10. Repeat all above steps for 3-4 values of wavelength.
11. Select correct choice from the result.
    a. Photoelectric current is *directly/inversely* proportional to light intensity.
    b. The slope of a graph *increase/decrease/remain constant* by increasing frequency (or decreasing wavelength).

B. A certain minimum frequency is required to emit photoelectron.

To observe this phenomenon:

1. Adjust the voltage between two plates V = 0 volt.
2. Set the wavelength knob on infrared region.
3. Set the intensity of incident light greater than 0%.
4. Now vary the wavelength from infrared to ultraviolet and note the wavelength when photoelectric effect is just started.
5. Calculate the corresponding frequency by using formula $c = \upsilon\lambda$. This is the minimum frequency required to emit photoelectron; called ***threshold frequency*** υ_0.
6. For accurate setting of ***threshold frequency*** you may set the value of wavelength using keyboard and then press the 'Enter' key.
7. Check accuracy by varying light intensity (from 0% to 100%) and varying voltage (from - 8V to + 8V).

8. By default, photosensitive material is ‘Sodium’, shown at right in the ‘Target’ window with ‘arrow’. If you click on the arrow, it gives list of various photosensitive materials.
9. Select another photosensitive material and find ***threshold frequency***.
10. Select correct choice from the observation.
    Threshold frequency is *depends/independent* on material structure.

C. Some points which cannot be explained by wave theory of light:

Point-1: A certain minimum frequency is required to emit photoelectron.

Try yourself to observe this phenomenon or Press ‘Step’ Button.

1. Adjust 0 volt between two plates.
2. Set the wavelength knob in infrared region.
3. Set intensity of incident light greater than 0%.
4. Now vary the wavelength from infrared to ultraviolet so that photoelectric effect is just started.
5. Note this wavelength and calculate the corresponding frequency by using formula $c = \upsilon\lambda$. This is the minimum frequency required to emit photoelectron (***threshold frequency*** υ_0).

Point-2: Velocity (or Kinetic Energy) of an emitted photoelectron is independent of intensity of the incident rays.

Try yourself to observe this phenomenon or Press ‘Step’ Button.

1. Adjust the wavelength of incident light $\lambda = 400$ nanometer.
2. Vary the intensity knob and select correct choice from the observation:
    - Numbers of photoelectrons *increase/decrease* by increasing intensity of incident beam but the velocity of photoelectrons (i.e. its Kinetic Energy) remains the same.
    - Thus a higher intensity beam emits *more/less* photoelectrons then a weak intensity beam of the same frequency, but the average energy of photoelectron is same or energy of photoelectron is *dependent/independent* on the intensity of incident ray.

Point-3: The velocity of emitted photoelectron increases by increasing frequency of the incident rays.

Try yourself to observe this phenomenon or Press ‘Step’ Button.

1. Keep the intensity constant and
2. Vary the wavelength and select correct choice from the observation:
    - As frequency increases (by moving knob from right to left) speed of photoelectron *increases/decreases*.

Point-4: As we observed there is no time lag between the arrival of light at a metal surface and the emission of photoelectron. According to classical theory, light energy is uniformly distributed over the wave front. Therefore to emit photoelectron, measurable time is required to absorb energy from the incident wave front.

Example:

A potassium plate is placed 1 meter from a feeble (weak) light source with power 1 W = 1 joule/sec. Assume that a ejected photoelectron may collect its energy from a circular area of the plate whose radius r is, say, one atomic radius $r = 1 \times 10^{-10}$ m. The energy required to remove an electron the potassium surface is about 2.1 eV = 3.4×10^{-19} joule. How long would it take for such a target to absorb this much energy from the light source? Assume the light energy to be spread uniformly over the wave front.

Solution:

The target area is $\pi \cdot r^2 = \pi \cdot 10^{-20} m^2$

The area of a 1 m sphere centered on the source is $= 4\pi(1 \cdot m)^2 = 4\pi \cdot m^2$

Thus if the source radiates uniformly in all directions (i.e. if the energy is uniformly distributed over a spherical wave front spreading out from the source, in agreement with the classical theory) the rate at which energy falls on the target is given by

$$rate = (1 \cdot joule/\sec) \cdot \frac{\pi 10^{-20} m^2}{4\pi \cdot m^2} = 2.5 \times 10^{-21}\, joule/\sec$$

Assuming that all this power is absorbed, we may calculate the time required for the electron to acquire enough energy to escape; we find

$$t = \frac{3.4 \times 10^{-19}\, joule}{2.5 \times 10^{-21}\, joule/\sec} = 1.4 \times 10^{2} \sec \cong 2 \min$$

D. Einstein explanation of the photoelectric effect:

To explain this phenomena Einstein applied Planck's Quantum theory and made the following assumptions

1. A radiation of frequency υ consists of discrete quanta each of energy $h\upsilon$, where h is Planck's constant. These quanta are called photon.
   To observe these phenomena Select middle options given at upper left-corner of the experimental screen then select 'Show photons'.
2. When a photon of energy $h\upsilon$ is incident on a metal surface, the entire energy of the photon is absorbed by a single electron without any time lag.

To observe these phenomena set:

1. Intensity = 1 or 2% and
2. Wavelength = 200 nm

3. The probability of absorbing two or more photons at the same time is negligible.

Einstein's quantum theory of the photoelectric effect:

For a given photosensitive material required a certain minimum frequency to emit photoelectron, called threshold frequency υ_0 .

This minimum energy of photon with frequency υ_0 required to remove electron from the metal is called ***work function*** *(W)* of the material. This work is needed to overcome the attractive fields of the atoms in the surface and loss of kinetic energy due to internal collisions of the electron.

$$W = h\upsilon_0 \qquad (1)$$

Photon with energy $h\upsilon$ (> *W*) incident on metal surface will emit photoelectron. Remaining energy of the photon ($h\upsilon$ -*W*) is transferred to the electron, which is converted into its kinetic energy; given by the equation

$$E = \frac{1}{2}mv_{\max}^2 = h\upsilon - W \qquad (2)$$

Where *m* is the mass of photoelectron and $v_{\max}$ is maximum velocity.

As we saw in the experiment that emitted photoelectron is just stopped by adjusting potential on collector plate, called stopping potential V_0. Thus energy of photoelectron in terms of stopping potential is

$$E = eV_0 \qquad (3)$$

Where e is charge on electron.

Equating equations (2) and (3)

$$eV_0 = \frac{1}{2}mv_{\max}^2 = h\upsilon - W$$

Now using equation (1)

$$eV_0 = h\upsilon - h\upsilon_0$$

$$V_0 = (h/e)\upsilon - (h/e)\upsilon_0$$

This is straight line equation with slope (h/e) and intersection on energy axis $-(h/e)\upsilon_0$ is the work function and intersection on frequency axis is threshold frequency υ_0 .

Some points which cannot be explained by wave theory can be explained by quantum theory as follows:

Point-1: A certain minimum frequency is required to emit photoelectron can be explained by quantum theory using equation (1).

Point-2 & 3: The velocity (or KE) of emitted photoelectron is independent on the intensity of incident rays but depends on frequency of incident rays. This can be explained by using equation (2).

In this equation work function W is constant for given material. Therefore KE (or velocity) of photoelectron is directly proportional to the frequency of incident rays and not dependent on the intensity. Because intensity of radiation can be defined as number of photons per unit cross-section per second while the energy of radiation depends only on frequency $(E = h\upsilon)$.

Point-4: As we observed there is no time lag between the arrival of light at a metal surface and the emission of photoelectron. But from above example, we saw, by considering classical theory, time required to emit photoelectron is ~ 2 min. So there is no way to explain this phenomenon with the help of quantum theory. According to quantum theory the energy of a photon is not distributed over an area as in wave theory. It is in the form of concentrated bundle. So when photon is incident on an electron, all its energy is absorbed by the electron without any time lag.

Thus it is not possible to explain photoelectric effect, except by considering a radiation of frequency υ consists of discrete quanta each of energy $h\upsilon$ (called photon).

Example:

*Calculate **Threshold frequency** υ_0 **for Potassium** with work function 2 eV.*

Threshold frequency

$$\upsilon_0 = \frac{W}{h} = \frac{2eV}{6.6256 \times 10^{-34}\ joule\sec}$$

Using 1 eV = 1.6022 x 10^{-19} *joule, we find*

$$\upsilon_0 = \frac{2 \times 1.6022 \times 10^{-19}\, joule}{6.6256 \times 10^{-34}\, joule \sec} = 4.82975 \text{ x } 10^{14} (\sec)^{-1}$$

Hence for potassium, to emit electron the threshold frequency is

υ_0 = 4.82975 x 10^{14} Hz

Example:

A potassium plate is placed 1 meter from a feeble (weak) light source with power 1 W = 1 joule/sec. Assume that a ejected photoelectron may collect its energy from a circular area of the plate whose radius r is, say, one atomic radius r = 1 x 10^{-10} m. The energy required to remove an electron the potassium surface is about 2.1 eV = 3.4 x 10^{-19} joule. How long would it take for such a target to absorb this much energy from the light source? Assume the light energy to be spread uniformly over the wave front.

Solution:

The target area is $\pi \cdot r^2 = \pi \cdot 10^{-20} m^2$

The area of a 1 m sphere centered on the source is $= 4\pi(1 \cdot m)^2 = 4\pi \cdot m^2$

Thus if the source radiates uniformly in all directions (i.e. if the energy is uniformly distributed over a spherical wave front spreading out from the source, in agreement with the classical theory) the rate at which energy falls on the target is given by

$$rate = (1 \cdot joule/\sec) \cdot \frac{\pi 10^{-20} m^2}{4\pi \cdot m^2} = 2.5 \times 10^{-21} joule/\sec$$

Assuming that all this power is absorbed, we may calculate the time required for the electron to acquire enough energy to escape; we find

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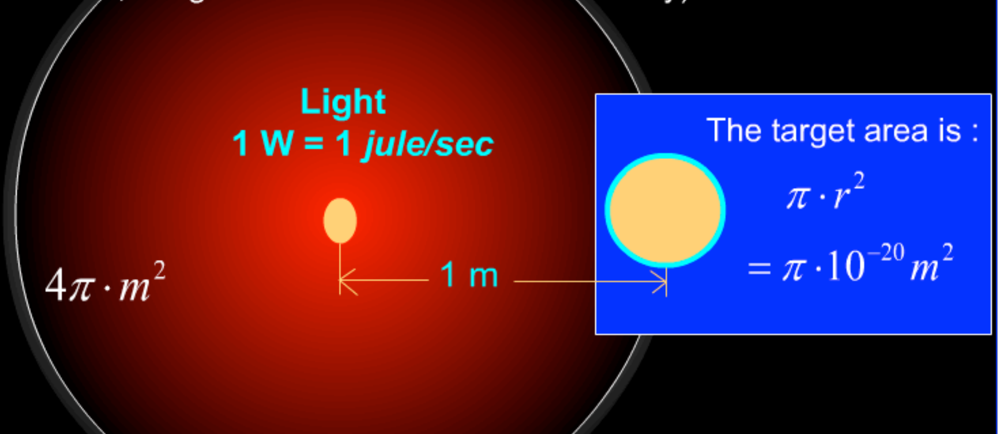
QM

Quantum Mechanics

Thus if the source radiates uniformly in all directions (i.e. if the energy is uniformly distributed over a spherical wave front spreading out from the source, in agreement with the classical theory)



The rate at which energy falls on the target is given by

$$rate = (1 \cdot joule/\sec) \cdot \frac{\pi 10^{-20} m^2}{4\pi \cdot m^2} = 2.5 \times 10^{-21} joule/\sec$$

Solution:

The target area is :

$\pi \cdot r^2 = \pi \cdot 10^{-20} m^2$

The area of a 1 m sphere centered on the source is :

$= 4\pi (1 \cdot m)^2 = 4\pi \cdot m^2$

Time required for the electron to acquire enough energy to escape:

$$t = \frac{2.1 \text{ ev} = 3.4 \times 10^{-19} J}{2.5 \times 10^{-21} J/\sec}$$

$$= 1.4 \times 10^2 \sec \cong 2 \min$$

Topic X ? T H