Section 4: Photoelectric Effect

The **photoelectric effect** is a phenomenon that occurs when light shone on a metal surface causes electrons to be emitted from the surface.

PhotoelectricEffectFacts

- Foragivenfrequencyoflight,thekineticenergyofthe electronsejectedfromametalsurfacewasthesame.
- Increasingthebrightnessofthelight(increasingtheamplitude) causedmoreelectronstobeejected;theirindividualenergies remainedthesame.
- Theenergyoftheemittedelectronswasdirectlyrelatedtothe frequencyofthelightstrikingthesurface.(Ifthefrequencyof incidentlightisincreased,thewavelengthofthelightwill decreaseandthekineticenergyoftheejectedelectronswill increase.)

ContradictionsbetweenthePhotoelectricEffectand WaveTheory

Thiseffectcompletelycontradictedthewavetheoryoflight: thatis,theenergyofinawaveisafunctionofitsamplitude. Increasingtheamplitudeorbrightness,shouldincreasethe energyoftheejectedelectrons.Howeverthiswasnotthecase. Einsteindecidedtoundertakeanexplanationofthephotoelectric effectfromatheoreticalpointofviewusingPlank'squantum idea.

Einstein'sWorkonthePhotoelectricEffect

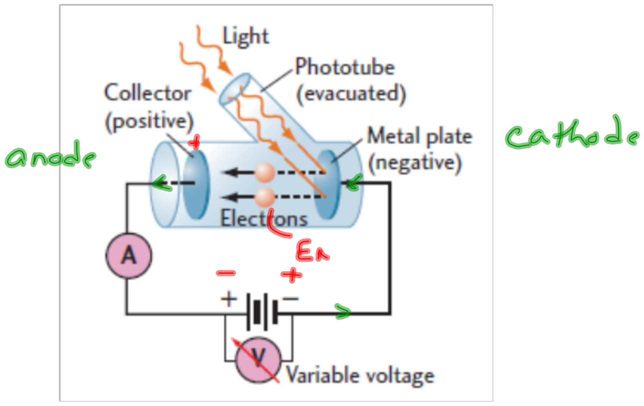
Albert Einstein explained the photoelectric effect based on Planck's quantum idea. For this work, he received a Nobel Prize in physics in 1921.

Einstein proposed that the photoelectric effect be a test of Planck's quantum hypothesis (ie. that **$E = hf$**, or that the energy of a quantum be directly proportional to its frequency). Einstein describes light as being many up of particles of energy called ***photons***. The photon theory of light predicts that each photon of incident light on a metal surface can strike an electron in the material and eject it if the photon has enough energy to do so. The maximum energy of the ejected electrons is then related to the frequency of the incident light.

Planck came up with the equation $E = hf$ by taking data from blackbody radiation experiments and "fitting" the equation to match the data. This match led the scientific community to the quantum theory. The photoelectric effect was viewed by Einstein as being a test of quantum theory. The test did indeed turn out to validate Planck's work.

The Apparatus

When light hits the negative metal plate electrons are bounced out of the plate. This is called the ***photoelectric effect***.



The photoelectric effect apparatus consisted of a shiny metal surface enclosed in a vacuum tube to prevent oxidation. When light was shone on the metal surface, some electrons were ejected from it. The metal being struck by the light was negative (the ***cathode***) and the terminal collecting the electrons was made positive (the ***anode***), so the electrons zipped from one terminal to the other as soon as they were liberated by the photons of light. The electrons streamed across to the collector plate because the voltage source in the external circuit made the collector plate positive. The anode and cathode were connected via a power supply providing a potential, and an ammeter that measured the amount of current.

Then the potential was reversed so that the anode became negatively charged, causing electrons to be repulsed from the anode. If the voltage (or potential) is increased (that is, if the collector plate is made more negative) the electrons will finally stop coming across.

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Note: The liberated electrons have kinetic energy while they are moving and potential energy when they are forced to stop.

According to the law of conservation of energy, the kinetic energy that has "disappeared" and the potential energy that has taken its place are equal.

So, the maximum kinetic energy of the ejected electrons (E_{kMax}) is equal to the electric potential energy required to prevent electrons from being ejected from metal surface. This potential energy is called the **stopping potential**, ***V*****stop**.

Recall: Electric Potential Energy is given by

E = qV For an electron *$q = e$ – the elementary charge*

So, **E = eV** In the case of the photoelectric effect, $V = V_{Stop}$

$\mathbf{E = eV_{Stop}}$

$E_{kmax} = eV_{stop}$

In other words, the electric potential energy of an electron that has just been stopped is $\mathbf{E = eV_{stop}}$ and this is equal to the kinetic energy that the electron use to have.

In equation form: $E_{k\,max} = eV_{stop}$

Summary:

- The kinetic energy of the electrons is measured by finding the minimum potential required to prevent electrons from being ejected from the metal surface. $E_{k\,max} = eV_{stop}$
- If the anode is positive, the electrons are attracted to the anode, causing current to flow.
- If the potential is reversed, the liberated electrons are repelled from the anode and no current flows.

Einstein applies Planck's Quantum Idea to Photoelectricity

- The photoelectric effect occurs when light strike a metal and electrons are ejected.
- This does not happen for just any old light.
- It will not happen for red light. Increasing the brightness (increasing the amplitude) of the red light will still not eject the electrons.
- So, contrary to what the wave theory would predict, **the amplitude is not an indication of the amount of energy that the light can give up to the electrons in the metal plate**.

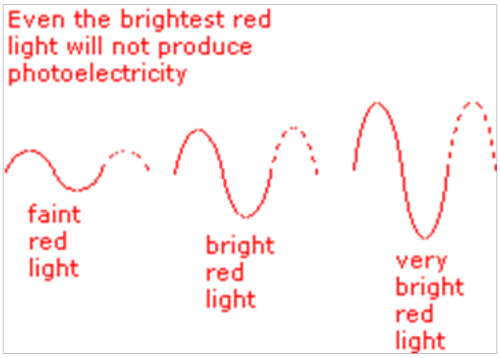
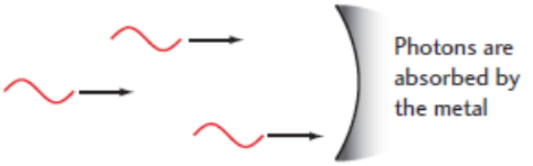


Fig.17.11A Lower-energy photons don't possess enough energy to liberate electrons from a metal surface



- The pictures to the right show three different brightness of blue light.
- Even the faintest blue light knocks electrons from the metal plate.
- As the light becomes brighter (greater amplitude), more and more electrons are emitted.

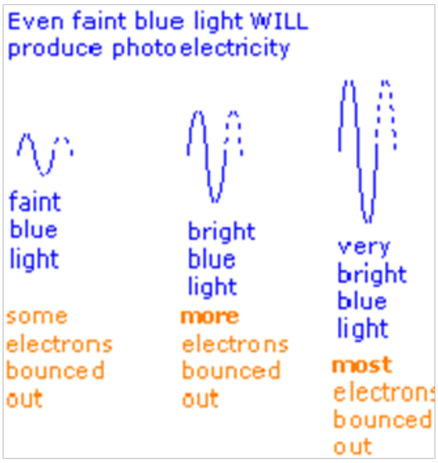
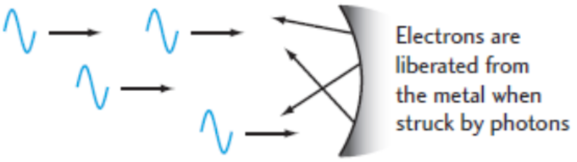


Fig.17.11B If a higher-energy photon hits the metal and is not reflected, it interacts with the electrons in the metal and transfers its energy to an electron. If the energy transferred by the photon is greater than the minimum energy required to evict the electron from the metal, then the electron will be emitted. The electron's kinetic energy is the energy of the photon minus the energy required to liberate the electron.



There are some conclusions to be drawn from the above observations:

- Since even the bright red light did not have enough energy to dislodge the electrons, but the faint blue light did, it must be that the ***energy*** of the in-coming light is ***governed by the frequency*** of the light and ***not by the amplitude*** of the wave (blue light has a higher frequency than red light).

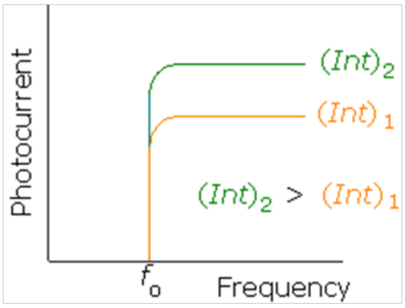
- If the light has high enough frequency to cause the photoelectric effect, then the ***brighter*** the light the ***more electrons*** knocked out of the metal.

- Since making the impinging blue light brighter increases the number of electrons, the number of photons in the light must govern the light's brightness. The **brighter the light, the more the photons, and each photon knocks out one electron.**

- If the frequency of the photons is not large enough to dislodge electrons, it makes no difference how many photons there are. That's why even bright red light does not cause a photoelectric effect.

- The photoelectric effect provides very good evidence that light is composed of tiny packets/bundles/quanta of energy. (Radiant energy was transmitted in bundles or quanta, each with a specific energy.)

A graph may help to sum up the above statements. The photocurrent graph below results from light of two different intensities $(Int)_1$ and $(Int)_2$ being shone on the same material. $(Int)_2 > (Int)_1$.



1 If the frequency of the impinging light is less than f_o, then no electrons will be liberated. In fact at $f = f_o$ the electrons are just barely liberated. ***f_o*** is the ***cut-off*** *or* ***threshold frequency***.

2 Once the threshold frequency has been exceeded, the **current** jumps to a maximum value which **depends on the intensity**. The larger the intensity the more incoming photons there are, and the more electrons will be liberated. The greater the intensity the greater the current will be. But for each light intensity the current will be constant as illustrated by the **horizontal lines** of the graph.

3 For a particular intensity, the **size of the current does not depend on the frequency of the incoming photons** This is illustrated by the horizontal parts as frequency increases on the x-axis. So, **increasing the frequency** does not increase the size of the current, but it **does increase the energy of each emitted electron**.

The Work Function

Imagine that you want to kick a soccer ball that is stuck in the sand on the beach. Your in-coming foot has so much energy which must be split into two bits: one bit does work to loosen the ball from the sand while the remaining energy moves the ball on its way (gives it some maximum amount of kinetic energy).

An electron being ejected from a metal surface is analogous to the soccer ball stuck in the sand.

The energy provided from an incoming photon ($\mathbf{E}_{(}$ **=hf**) serves two functions:

- The first is that it does work to free electrons. This aspect of the energy is referred to as the work function, $\mathbf{W_o}$.
- The remaining energy of the photon provides the freed electron with kinetic energy $\mathbf{E_{kmax}}$.

So, the Energy of the incoming photon is equal to the work function plus the kinetic energy of the electron

$\mathbf{E_\gamma = hf = W_O + E_{Kmax}}$

or

$\mathbf{(hc)/\lambda = E_{k\,max} + W_o}$

The **maximum amount of kinetic energy** of the emitted electron is always **less than the energy of the impinging photon** because some of the photon energy is used up to liberate the electron from the metal.

$E_{k\,max} = hf - W_o$

or

$\mathbf{E_{K\,max} = E_{photon} - W_o}$

The work required to liberate each electron is W_o and Einstein gave it the name **work function.**

The Stopping Potential Revisited

Recall that the stopping potential was that applied reverse potential that prevented the electrons from reaching the collector plate. For each electron with charge *e*, the stopping potential gives each electron an electric potential energy, $E = eV_{stop}$,

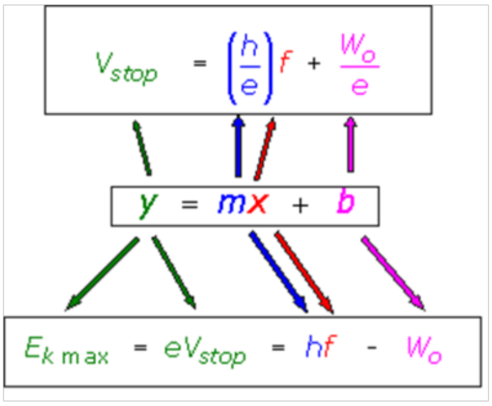
and that potential energy is just equal to the kinetic energy lost by the electron

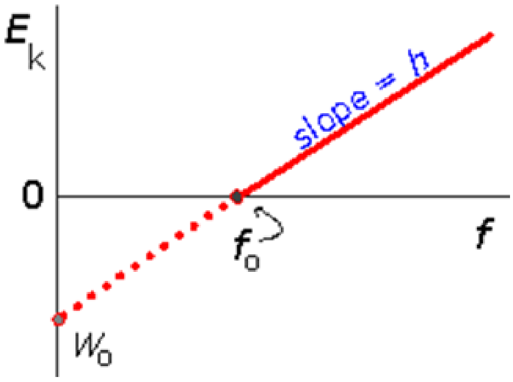
$\mathbf{E_{k\,max} = eV_{stop}}$

But $\mathbf{E_{k\,max} = hf - W_o}$

So, $\mathbf{eV_{stop} = hf - W_o}$

Solving this expression for V_{stop} gives: $V_{stop} = \left(\frac{h}{e}\right) f + \frac{W_o}{e}$.





We will look more closely at $E_{k\,max} = eV_{stop} = hf - W_o$

- slope is h
- y-intercept is $-W_o$.

The graph crosses the x-axis at $E_k = 0$ and frequency equal to a special frequency called f_o, the **cut-off or threshold frequency** . If the frequency of the impinging light is less than f_o, then no electrons will be liberated. In fact at $f = f_o$ the **electrons are just barely liberated**. All of the photon energy is used up in the work function (W_o) just to break them free and no energy is left over to give the electrons kinetic energy. You can see from the equation that when $E_k = 0$,

$W_o = hf_o$
or
$W_o = (hc) / \lambda$.

Therefore, in order for the photoelectric effect to occur, the energy of the incident photon must be greater than the work function: $E_{photon} > W_o$.

Relationship between Incident Photon Energy and Work Function

1. If $E_\gamma = hf = \frac{hc}{\lambda} < W_o$, then no electrons are emitted.
2. If $E_\gamma = hf = \frac{hc}{\lambda} = W_o$, electrons are not ejected (or just barely liberated)
3. If $E_\gamma = hf = \frac{hc}{\lambda} > W_o$, then electrons are ejected.

Examples

1 A certain metal with a known work function of 2.8 eV is shone with light of wavelength 625 nm. Will the photoelectric phenomenon be observed?

The photoelectric phenomenon will be observed only if the incoming photons have enough energy to free the electrons from the surface of the metal. That is, E_{photon} must be at least equal to the work function W_{o}.

2 For the material of question 1, what is the wavelength that will just manage to free electrons from the surface of the metal?

As you know, it is the larger frequencies that have enough energy to liberate the electrons. Since large frequency means small wavelength, another way to ask the question is "beyond what wavelength must the photon **not go** and still be able to liberate electrons?" or better still "what is the maximum wavelength that will force electrons to escape?"

The question could have been this: "what is the cut-off or threshold frequency for a material that has a work function of 2.8 eV?"

3 When an ultraviolet wave with wavelength 126 nm strikes a certain metal, the reversing or stopping potential that brings the photoelectric current to 0 is 4.2 V. Do the necessary calculations and then use the information in Table 17.1 on p. 704 of your text to determine the type of metal in the emitter plate.

4 When electromagnetic radiation with a wavelength of 200 nm falls on a metal, the maximum kinetic energy of the ejected electrons is 2.50 eV. What is the work function of the metal?

Practice

1. Which statement is false?

a) In a photoelectric current, electrons received their energy from electromagnetic radiation

b) The number of electrons in a photoelectric current depends on the brightness of the light

c) The brighter the light the greater the kinetic energy of the electrons

d) An intense beam of 250 nm uv radiation will provide photoelectrons with the same kinetic energy as will a faint beam of 250 nm uv radiation

2. Which statement is true?

a) a photoelectric current exists when $E_{\text{photon}} = W_o$

b) a photoelectric current exists when $E_{\text{photon}} - W_o < 0$

c) a photoelectric current exists when $W_o > E_{\text{photon}}$

d) a photoelectric current exists when $E_{\text{photon}} > W_o$

3. If you do not detect a current in your photoelectric apparatus, which of the following would be a sensible option?

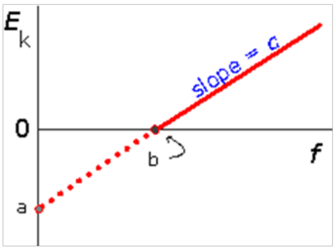
a) decrease the frequency of the impinging light

b) decrease the wavelength of the impinging light

c) increase the brightness of the impinging light

d) decrease the brightness of the impinging light

4. What is the correct description of the graph?



a) a = the work function, b = the threshold frequency, c = Planck's constant

b) a = the threshold frequency, b= Planck's constant, c = the threshold frequency

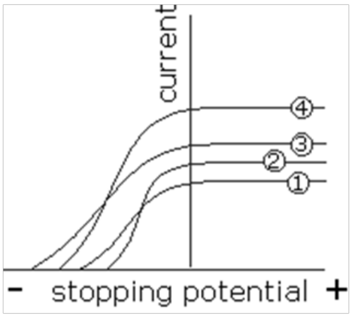
c) a = the work function, b= Planck's constant, c = the threshold frequency

d) a= Planck's constant, b = the threshold frequency, c = the work function

5. For a certain metal the work function is 2.3 eV and the incoming photons have energy of 5.1 eV. What will be the maximum kinetic energy of the emitted electrons?

   a) 2.8 eV b) 2.2 eV c) 11.7 eV d) 7.4 eV

The graph below shows the photocurrent resulting from 4 different frequencies of incident light on the same emitter material. Note that each frequency pre-determines the magnitude of stopping potential that causes the current to drop to zero. Use the graph to answer questions 6 to 9.



6. Which incident light had the lowest frequency?
   a) 1 b) 2 c) 3 d) 4

7. Which beam of light ejected electrons with the highest energy?
   a) 1 b) 2 c) 3 d) 4

8. Which incident light was the brightest?
   a) 1 b) 2 c) 3 d) 4

9 What is the stopping voltage of an electron that has 8.5×10^{-19} J of kinetic energy?

10 Light, with a frequency of 6.0×10^{14} Hz, illuminates a photoelectric surface that has a work function of 3.2×10^{-19} J. What is the maximum kinetic energy of the ejected electron?

11 When electromagnetic radiation with a wavelength of 350 nm falls on metal, the maximum kinetic energy is 1.20 eV. What is the work function of the metal?

12 What is the energy of a photon that has a wavelength of 460 nm?

13 What is the stopping voltage of an electron that has 7.4 x $10^{-19\ J}$ of kinetic energy?

14 Light, with a frequency of 5.0 x 10^{14} Hz, illuminates a photoelectric surface that has a work function of 2.3 x 10^{-19} J. What is the maximum energy of the ejected electrons?