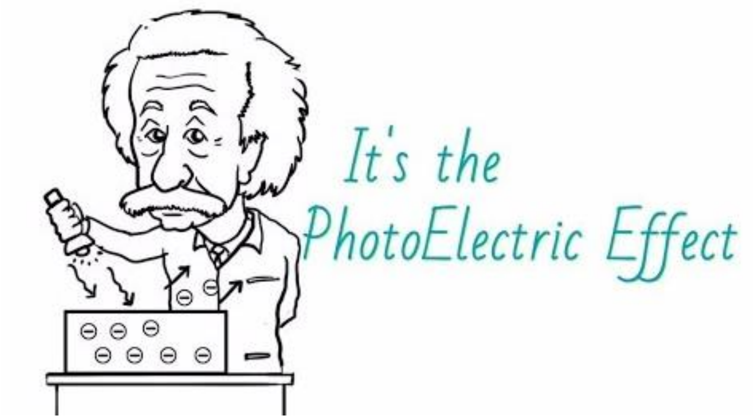
MODULE 7 NATURE OF LIGHT

Quantum Model

Einstein's Hypothesis:

Photoelectric Effect

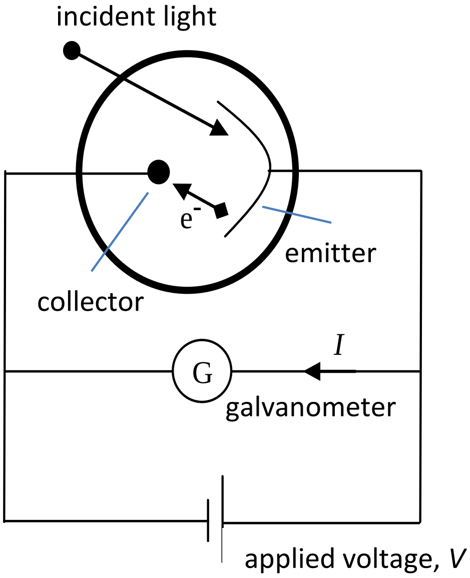


The photoelectric effect was discovered by Hertz in 1887 as he confirmed Maxwell's electromagnetic wave theory of light. In the **photoelectric effect**, incident electromagnetic radiation (light) shining upon a material transfers energy to electrons so that they can escape from the surface of the material.

Electromagnetic radiation acts on electrons within metals, increasing their total energy. Because electrons in metals are weakly bound, you would expect that light would give electrons enough extra kinetic energy to allow them to escape from the metal's surface. The released electrons are often referred to as **photoelectrons**.

The minimum extra kinetic energy that allows electrons to escape the material is the called the **work function** W_{min}. The work function is the minimum binding energy of an electron to the material.

Experimental results of the photoelectric effect



Experiments around 1900 showed that when visible and ultraviolet light were incident upon a clean metal surface, electrons were ejected from the surface. Experiments used an evacuated tube known as a photocell. The light incident upon an emitter electrode ejected the electrons, producing an electric current *I* that was measured using a sensitive galvanometer. A voltage was applied between the emitter and collector electrodes. The polarity of this voltage could be reversed to either accelerate the photoelectrons from the emitter to the collector or retard their movement and prevent them reaching the collector electrode.

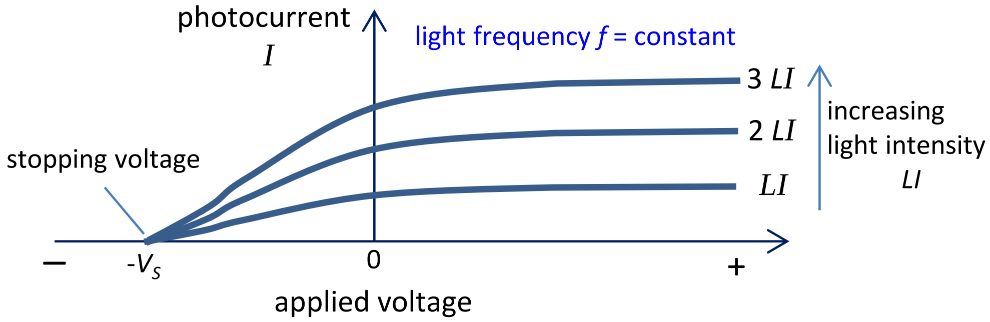
When the applied voltage was such that collector was negative, it could be adjusted to set the current measured by the galvanometer to zero ($I = 0$). This voltage is called the **stopping voltage** V_S.

Classical theory on electromagnetic radiation predicts that electrons would be ejected from a material as the electrons absorb energy from the incident electromagnetic wave.

Waves transfer energy: the larger the amplitude of the wave, the greater energy possessed by the wave. The water waves slowly erode the cliff face. In classical theory it was expected that electromagnetic waves incident on a metal surface would interact with electrons like water waves eroding the cliff face. But this was not supported by experimental observations.

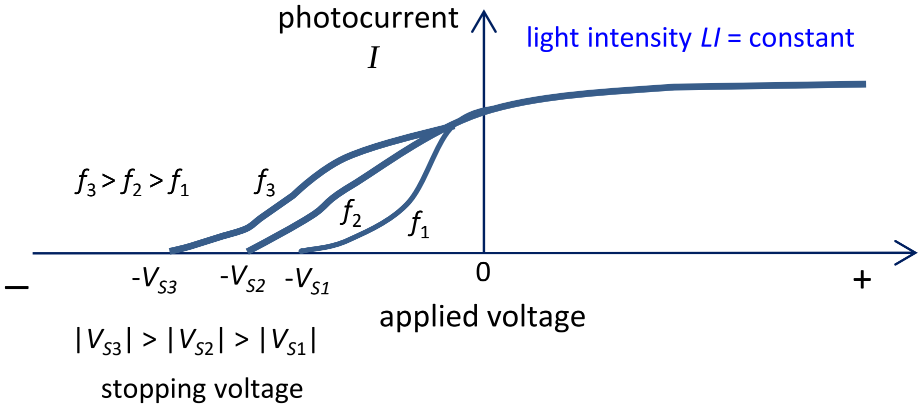
Key experimental finding (many of which were very surprising in terms of classical physics predictions):

1. The kinetic energies of the photoelectrons are independent of the intensity of the incident light. A given stopping voltage V_s stops all photoelectrons from reaching the collecting electrode (I = 0), no matter what the intensity of the light. For a given light intensity, there is a maximum photocurrent reached as the applied voltage increases from negative to positive.



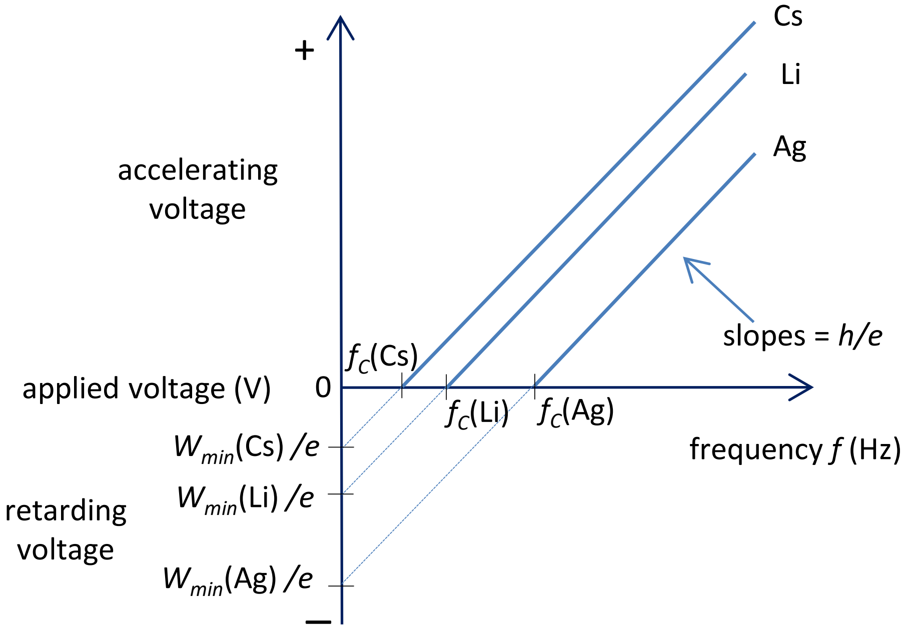
☒ Classical theory: The greater the amplitude of the wave then the greater the energy and intensity of the wave. Therefore, electrons should be ejected with more kinetic energy as the light intensity increases. Key finding #1 can't be explained by classical theory.

2. The maximum kinetic energy of the photoelectrons depends only of the frequency *f* of the light for a given material. Hence, a different stopping voltage is required for different frequencies: the greater the frequency, the larger the stopping voltage to reduce the photocurrent to zero. The value of V_s depends on the frequency *f* of the light and not on its intensity *LI*.



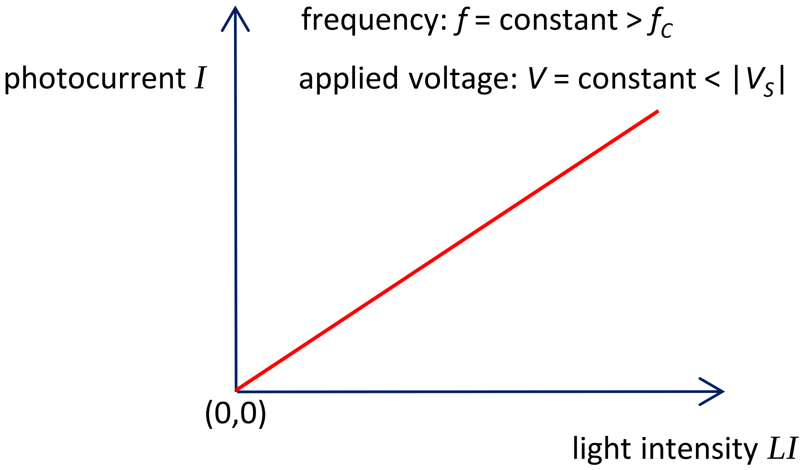
☒ Classical theory: The greater the amplitude of the wave then the greater the energy and intensity of the wave. Therefore, electrons should be ejected with more kinetic energy as the light intensity increases. Key finding #2 can't be explained by classical theory because the maximum kinetic energy of the photoelectrons depends on the value of the light frequency and **not** the intensity.

3. If the frequency of the incident is too small, zero electrons are ejected from the emitter electrode, no matter how large the intensity of the incident light. A photocurrent is only observed when the frequency of light is greater than some threshold value, called the **critical frequency** f_C. The smaller the work function W_{min} of the material, the smaller the value of the critical frequency f_C.



☒ Classical theory: the existence of a threshold frequency is completely inexplicable as are the results for the linear relationship between applied voltage and frequency as shown in the above graph.

4. When photoelectrons are emitted from the emitter electrode, their number is proportional to the intensity of the light, hence, maximum photocurrent is proportional to the light intensity.



☑ Classical theory does predict that the number of photoelectrons ejected will increase with intensity.

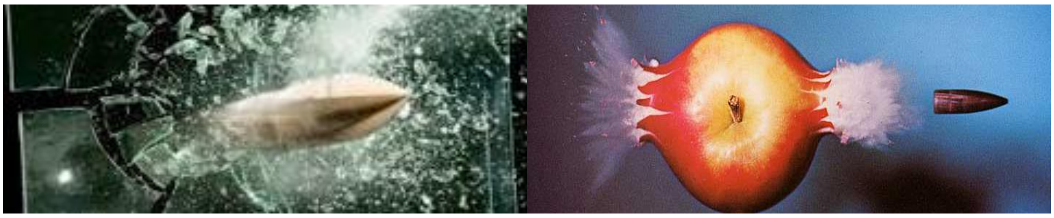
5. Photoelectrons are emitted almost instantly (< 3×10^{-9} s) following the illumination of the emitter electrode, and this time is independent of the intensity of the light.

☒ Classical theory would predict that for low light intensities, a long time would elapse before any one electron could obtain sufficient energy to escape.

The German physicist Philipp Lenard won the 1905 Noble Prize for his experimental research on the photoelectric effect and on the behaviour of electrons.

Quantum Interpretation and Einstein’s Theory

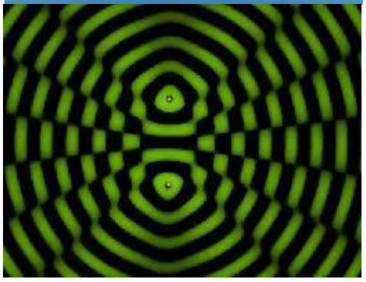
To explain the experimental observations of the photoelectric effect, it was necessary to model the incident electromagnetic wave as a stream of particles. The light interacting with the electrons in the material is like a stream of bullets hitting a target.



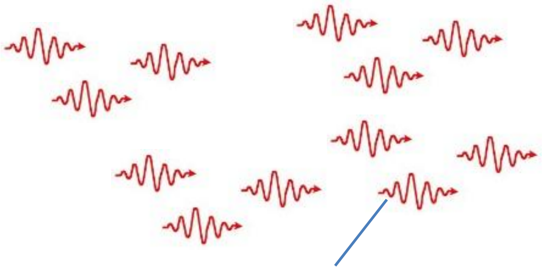
Einstein took Planck’s idea about quantization of energy for an oscillator a step further and suggested that the electromagnetic radiation field is itself quantized and that the energy of a beam of light spreading out from a source is not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space which move without dividing, and which can only be produced and absorbed as complete units.

Continuous waves spreading out from a single disturbance

Interference of wave fronts from a double disturbance



Electromagnetic radiation has particle-like properties: it can be considered a stream of particles called photons that travel at the speed of light *c*, and the energy of each photon is $h f$



quantum or bundle of energy $h f$

These quantized energy units of light are called **photons**. Each individual photon has an energy quantum

(1) $E = h f$

Energy of photon, E [joule J]

Frequency of electromagnetic radiation, f [hertz Hz $\equiv$ s^{-1}]

Planck's constant, $h = 6.6261\text{x}10^{-34}$ J.s

Einstein's proposal meant that as well as light behaving as a **wave** as shown by its interference effects, light must also have a **particle-like** aspect.

To explain the photoelectric effect, each photon delivers its entire energy $h\,f$ to a single electron in the material. For an electron to be ejected from the material, the photon's energy must be greater than the energy binding the electron to the material. If the photons energies are less than the binding energies, zero electrons can be emitted from the material, irrespective of how intense the incident light beam. Hence, using the principle of conservation of energy

Energy before (photon) E

= Energy after (ejection of electron from material W + K.E. of ejected electron E_K)

(2) $E = h\,f = W + E_K$

When the energy required to remove an electron from the material is a minimum W_{min}, (W_{min} is the **work function** of the material), the kinetic energy of the ejected electron will be a maximum E_{Kmax}, hence,

(3a) $h\,f = W_{\min} + E_{K\max}$

(3b) $h\,f = W_{\min} + \tfrac{1}{2} m_e\, v_{\max}{}^2$

The applied potential can be used to retard the electrons from reaching the collector. The retarding voltage, when the photocurrent *I* becomes zero, is called the **stopping voltage** and its value can be used to measure the maximum kinetic energy of the photoelectrons

(4) $$eV_S = \tfrac{1}{2} m_e v_{\max}{}^2$$

Einstein's quantum interpretation can explain all the details of photoelectric effect experiments.

Key findings #1 and #2 are easily explained because the kinetic energy of the electrons does not depend upon the light intensity at all, but only on the light frequency and work function of the material.

(5) $$\tfrac{1}{2} m_e v_{\max}{}^2 = h\,f - W_{\min}$$

A potential slightly more positive than $-V_S$ will not be able to repel all electrons and a small current will be measured. As the applied voltage increases in a positive sense the current will increase until most of the electrons will be collected and the current will be at a maximum. If the light intensity increases, there will be more photons ejecting electrons, and therefore a higher photocurrent as shown in graph for #1. If a different frequency is used, then a different stopping voltage is needed to stop the most energetic photoelectrons. The higher the incident light frequency, then, the greater the magnitude of the stopping voltage, as shown in graph for #2.

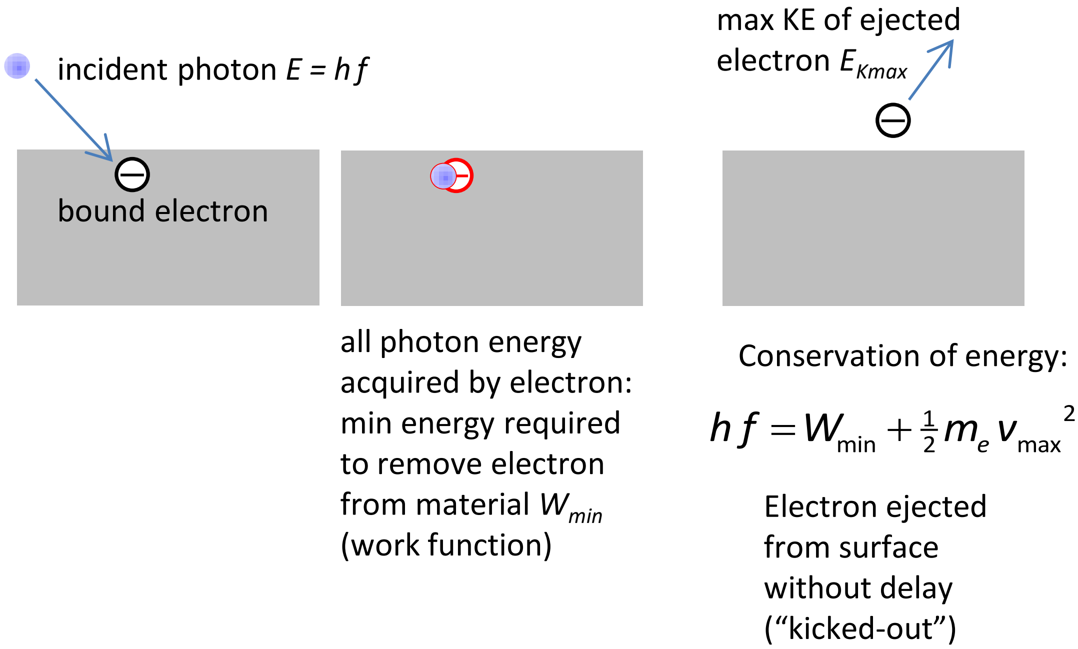
Key finding #3: Equations (3) and (4) can be rearranged to give a linear relationship between the stopping voltage and the light frequency, hence the quantum explanation accounts for the results shown in graph #3.

$$(5) \quad V_S = \left(\frac{h}{e}\right) f - \frac{W_{\min}}{e}$$

From the linear graph of equation (5) when V_S is plotted against f, the slope (h/e) can be used to estimate the value of Planck's constant h and the Y-intercept (W_{min} / e) to give the value of the work function W_{min} of the material. The X-intercept corresponding to $V_S = 0$ gives the value for the critical frequency $f_C = W_{min} / h$.

Key finding #4: The number of photons increases in proportion to the increase in light intensity. Hence, increasing light intensity means more photons, hence more photoelectrons released and a higher photocurrent measured as shown in graph #4.

Key finding #5: Electrons will be ejected from the material without delay because an electron will absorb all the energy from an individual photon, thus, it is "kicked out" almost immediately.



incident photon $E = hf$

bound electron

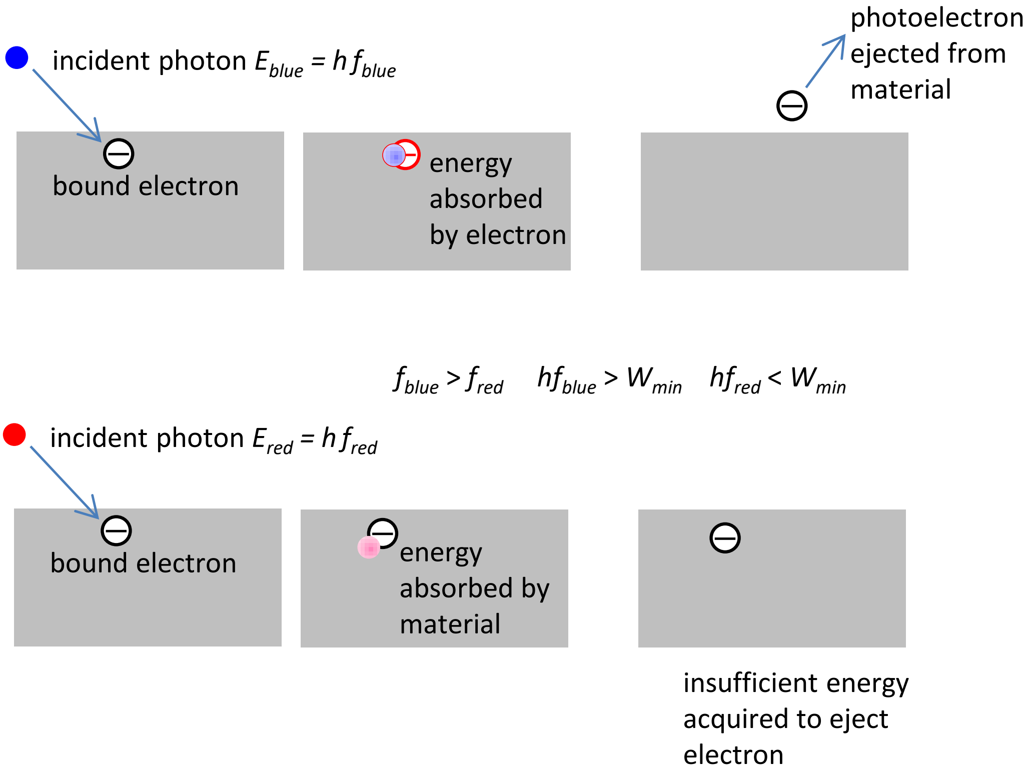
all photon energy acquired by electron: min energy required to remove electron from material W_{min} (work function)

max KE of ejected electron E_{Kmax}

Conservation of energy:

$$hf = W_{\min} + \tfrac{1}{2} m_e v_{\max}^2$$

Electron ejected from surface without delay ("kicked-out")



incident photon $E_{blue} = hf_{blue}$

bound electron

energy absorbed by electron

photoelectron ejected from material

$f_{blue} > f_{red}$ $hf_{blue} > W_{min}$ $hf_{red} < W_{min}$

incident photon $E_{red} = hf_{red}$

bound electron

energy absorbed by material

insufficient energy acquired to eject electron

Einstein’s theory of the photoelectric effect proposed in 1905, was gradually accepted after 1916 and finally he received the Nobel Prize for the year 1921, primarily for his explanation of the photoelectric effect (not for his Special Relatively theory).

Summary

Electromagnetic radiation consists of photons which are particle-like (or corpuscular) entities traveling at the speed of light *c* and consisting of energy *E*

(6) $c = f\,\lambda$ $c = 2.9979\text{x}10^{8}\ \text{m.s}^{-1}$

(1) $E = h\,f$

The total energy in the beam of light is the sum total of the energy of all the photons and for monochromatic light (unique wavelength λ) is an integral multiple of $h\,f$.

(7) $E_{beam} = N\,h\,f$

monochromatic beam of light

N = number of photons in beam

This representation of the photon picture must be true over the entire electromagnetic spectrum from radio waves to visible light, UV, X-rays and gamma rays.

Every particle that has energy must also have momentum, even if it has zero rest mass. Photons have zero rest mass. The energy *E* and momentum *p* of a photon with frequency *f* and wavelength λ are

$$E = p\,c \qquad E = h\,f \qquad c = f\,\lambda \qquad p = \frac{E}{c} = \frac{hf}{f\,\lambda} \qquad p = \frac{h}{\lambda} \tag{8}$$

The direction of the photon's momentum is simply the direction in which the electromagnetic wave is moving.

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If you have any feedback, comments, suggestions or corrections please email:

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