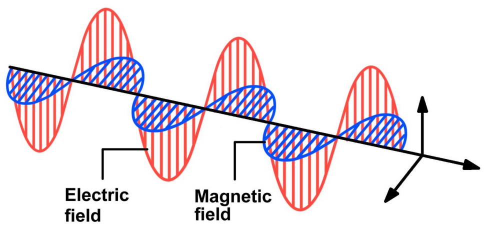
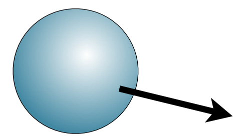
Chapter 3: Particle Properties of Electromagnetic Radiation



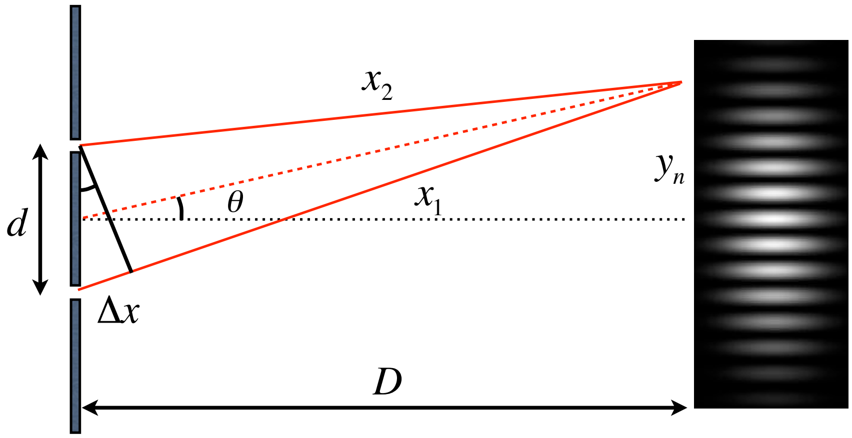
EM Wave



Photon

3.1 Evidence that Light is a Wave.

Double Slit Experiment: Interference of two coherent waves



$$\sin\theta \approx \frac{y_n}{D} \approx \frac{\Delta x}{d}$$

constructive interference

$$\Delta x = n\lambda$$

$$y_n \approx n\frac{\lambda D}{d}$$

$$d\sin\theta \approx n\lambda$$

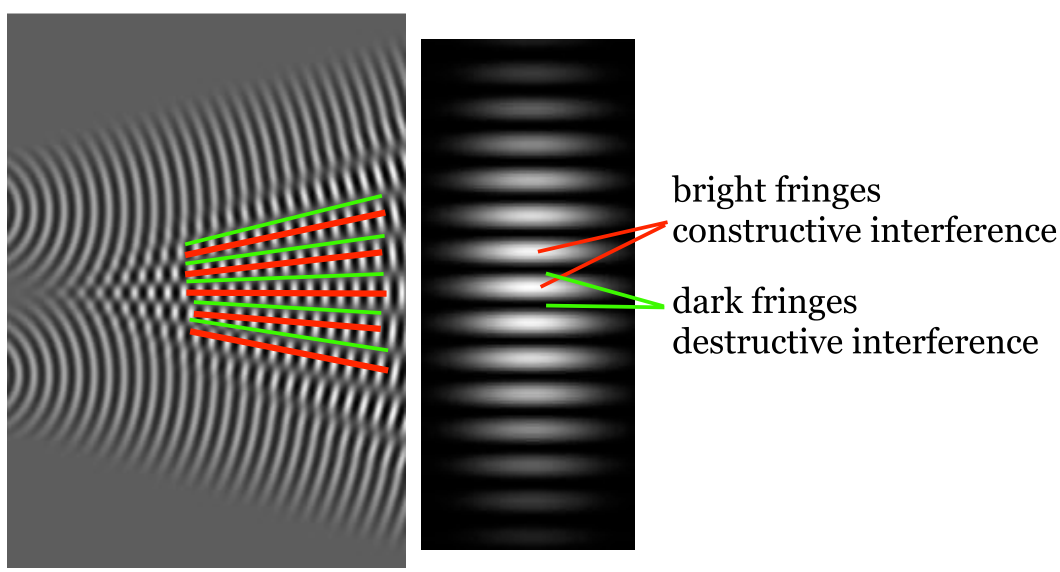
destructive interference

$$\Delta x = \left(n + \tfrac{1}{2}\right)\lambda$$

$$y_n \approx \left(n + \tfrac{1}{2}\right)\frac{\lambda D}{d}$$

$$d\sin\theta \approx \left(n + \tfrac{1}{2}\right)\lambda$$

Double Slit Experiment: Interference of two coherent waves



constructive interference

$$\Delta x = n\lambda$$

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destructive interference

$$\Delta x = \left(n + \tfrac{1}{2}\right)\lambda$$

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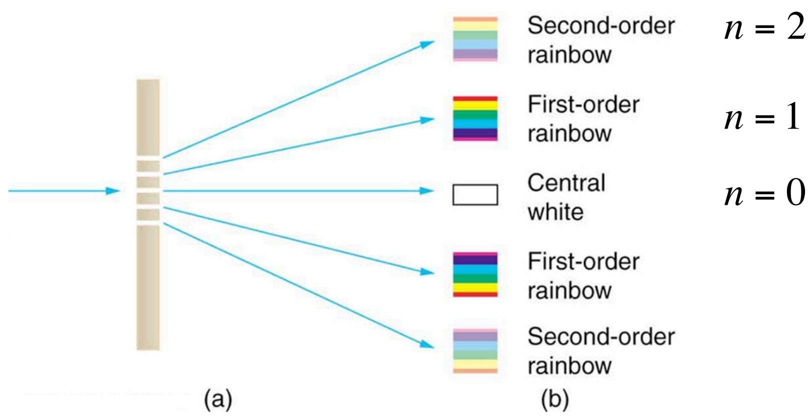
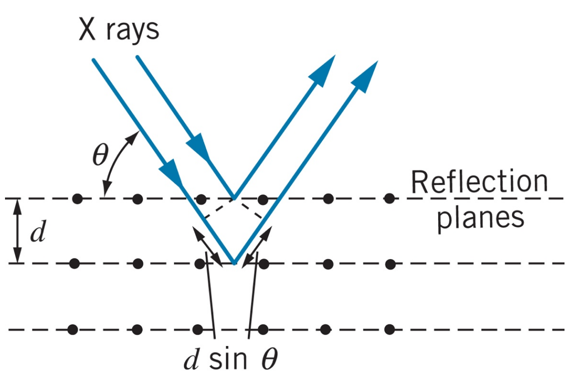
Diffraction Grating

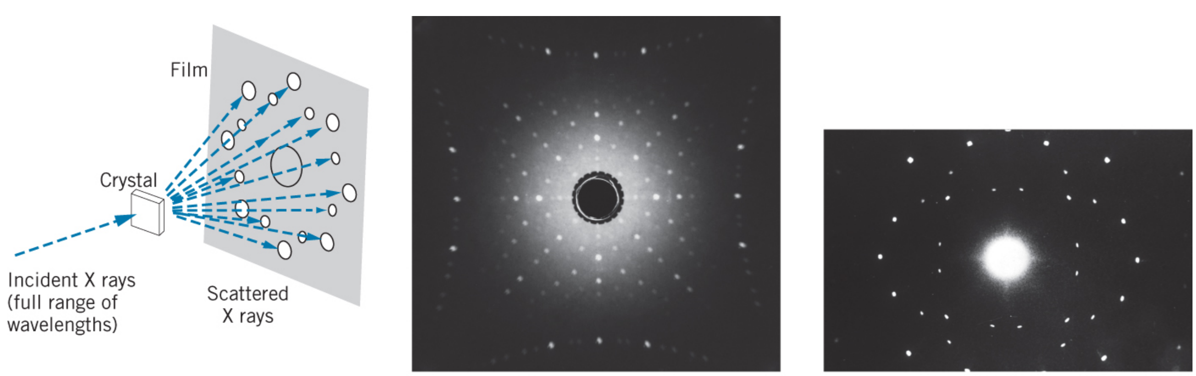


$$d \sin\theta = n\lambda$$

Crystal Diffraction of X-rays

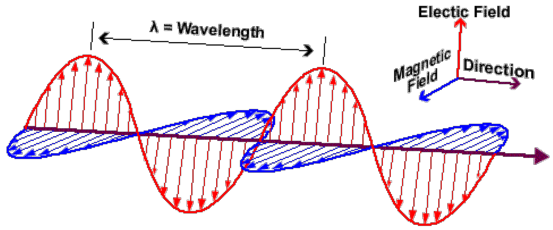


$$2d \sin\theta = n\lambda$$



(a) *(b)* *(c)*

Electromagnetic Waves



Electric & Magnetic Fields

$$\mathbf{E}(x,t) = \mathbf{E}_0 \sin(kx - \omega t)$$
$$\mathbf{B}(x,t) = \mathbf{B}_0 \sin(kx - \omega t)$$

Intensity (power/area)

$$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B}$$

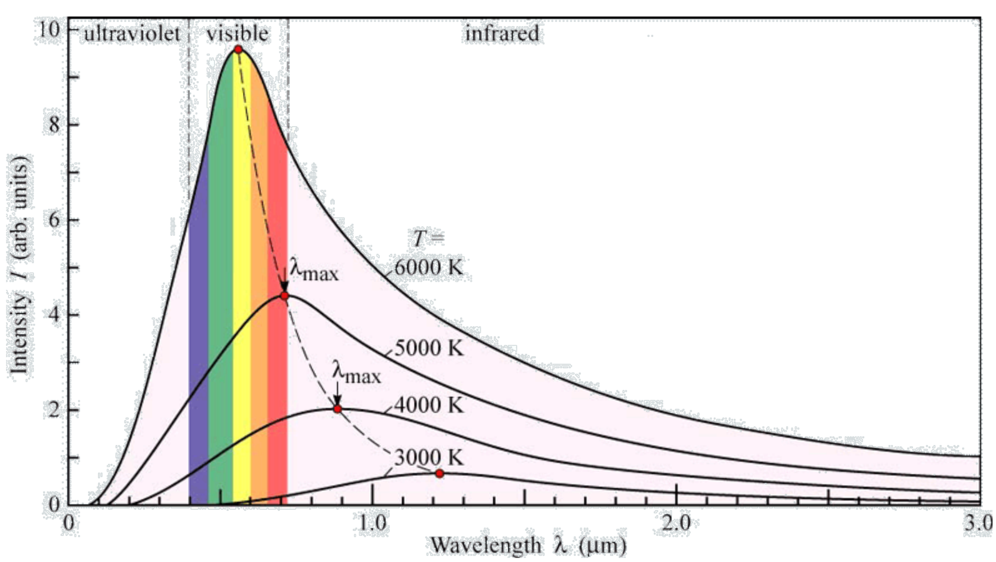
Time-averaged Intensity

$$I = \frac{E_0^2}{2\mu_0 c}$$

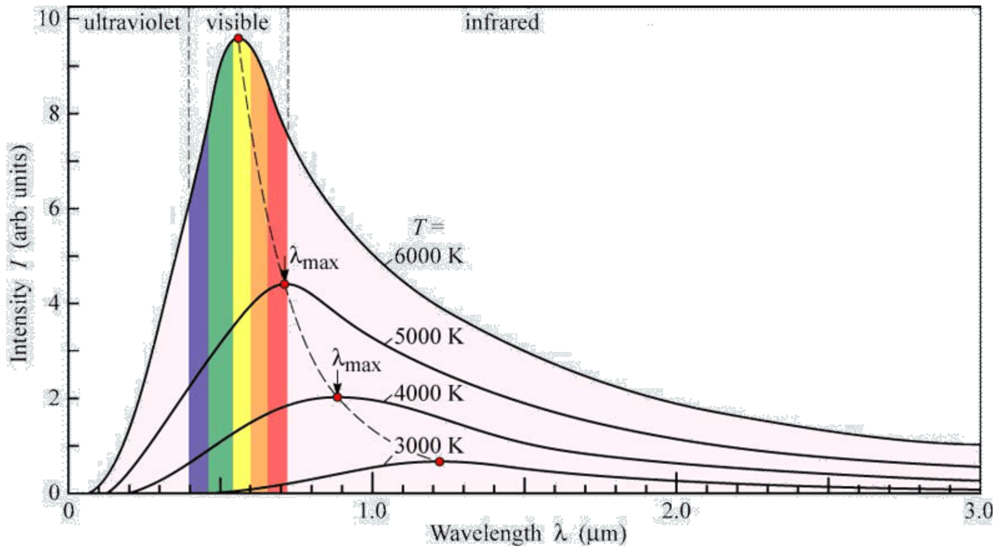
Properties of electromagnetic waves:

1. Intensity (i.e. brightness or power/area) of wave is proportional to the square of the amplitude
2. The intensity fluctuates sinusoidally in time with frequency $2f = 2\left(\frac{\omega}{2\pi}\right)$

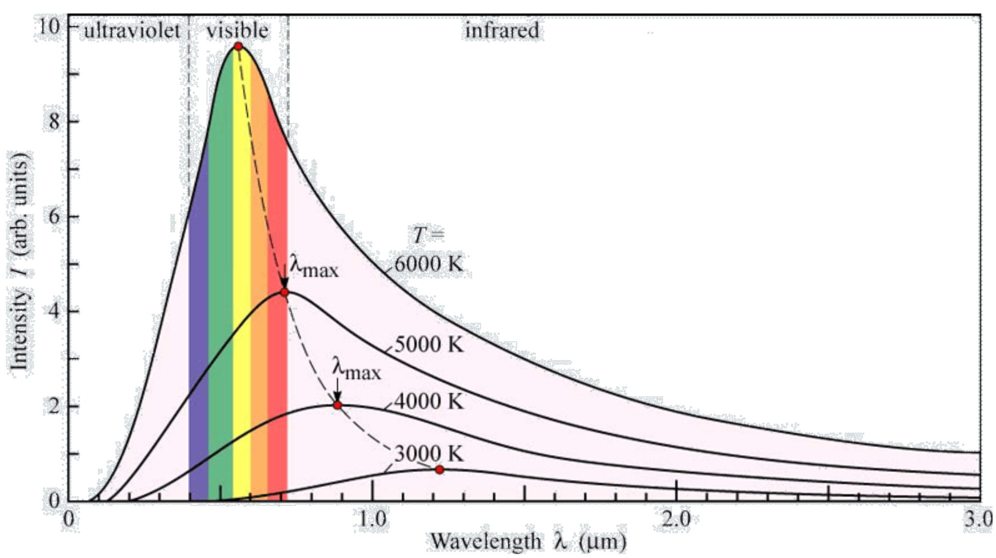
3.3 Thermal Radiation



3.3 Thermal Radiation



3.3 Thermal Radiation



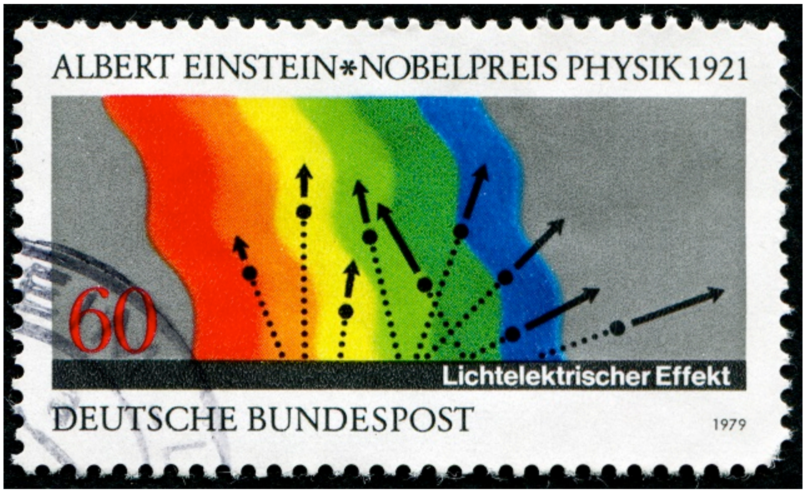
3.3 Thermal Radiation

Quantity	Classical	Quantum
# of modes per unit volume	$n = \dfrac{8\pi}{\lambda^4}$	$n = \dfrac{8\pi}{\lambda^4}$
Mode energy	E (continuous variable)	$E_n = nhf$ (quantized variable)
Distribution function	$f(E) \propto e^{-E/kT}$	$f(E_n) \propto e^{-E_n/kT}$
Ave. energy per mode	$\bar{E} = \dfrac{1}{N}\displaystyle\int_0^\infty E\, f(E)\, dE$	$\bar{E} = \dfrac{1}{N}\displaystyle\sum_{n=0}^{\infty} E_n f(E_n)$
	$= \dfrac{1}{kT}\displaystyle\int_0^\infty E\, e^{-E/kT}\, dE$	$= A \displaystyle\sum_{n=1}^{\infty} E_n e^{-E_n/kT}$
	$= kT$	$= \dfrac{hc/\lambda}{e^{hc/\lambda kT} - 1}$
Energy density	$u = n \cdot \bar{E}$	$u = n \cdot \bar{E}$
	$= \left(\dfrac{8\pi}{\lambda^4}\right)(kT)$	$= \left(\dfrac{8\pi}{\lambda^4}\right)\left(\dfrac{hc/\lambda}{e^{hc/\lambda kT} - 1}\right)$
Final Result	$u = \dfrac{8\pi}{\lambda^4} kT$	$u = \dfrac{8\pi hc/\lambda^5}{e^{hc/\lambda kT} - 1}$

3.2 Photoelectric Effect

Photoelectric Effect

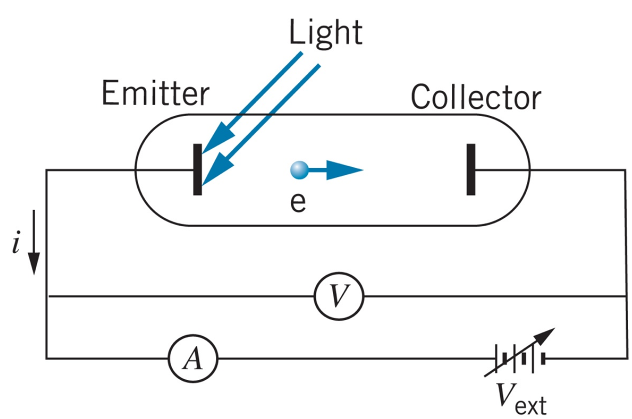
Shine light on a metal. Electrons come flying out.



Vary: (1) wavelength of light (2) Intensity of light

Observe: (1) electron current, (2) max K.E. of electrons

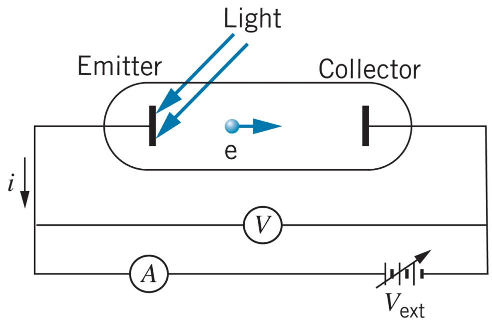
Photoelectric Effect



$$K_{\max} = eV_{stop}$$

Maximum K.E. = Stopping Potential

Photoelectric Effect - Experimental Results



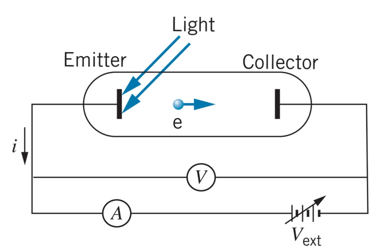
$$K_{\max} = eV_{stop}$$

What does the experiment show?

1. Photo-electrons appear almost instantaneously after light turned on
2. Photo-electrons only emitted when frequency of radiation is above a threshold value f_c
3. Max kinetic energy $K_{\max}$ does not depend on intensity of radiation

Photoelectric Effect - Experimental Results

1. Photo-electrons appear almost instantaneously (< 1 ns) after light turned on



How long would it take an atom to absorb enough energy to overcome the work function of the metal assuming classical physics?

Assume: Intensity $I = 100$ W/m^2

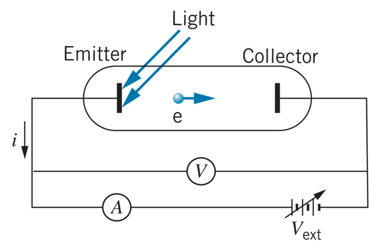
Work function $\phi = 2$ eV

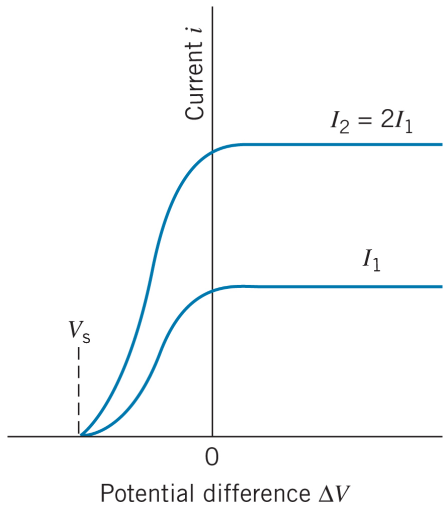
Cross section $A = \pi r_{atom}^2$

18 min

Photoelectric Effect - Experimental Results

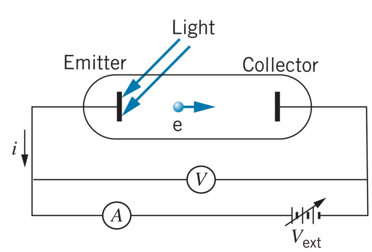
2. Max kinetic energy K_{max} does not depend on intensity of radiation

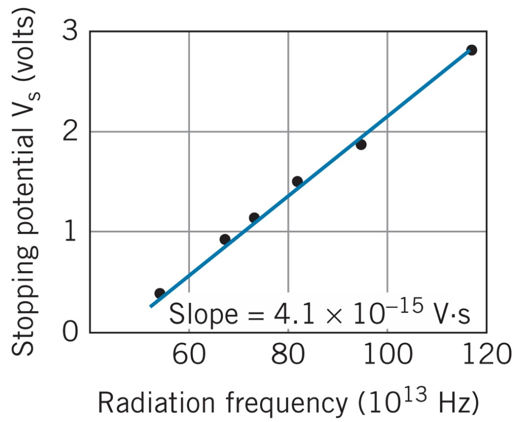




Photoelectric Effect - Experimental Results

3. Photo-electrons only emitted when frequency of radiation is above a threshold value f_c





Photoelectric Effect - Compare to Classical Prediction

Classical Prediction	Experiment
$K_{max} \propto I$ Max kinetic energy of electrons proportional to intensity of radiation	Max kinetic energy of electrons does not depend on intensity of radiation
Emitted electrons should be produced for any frequency of the radiation	Electrons only emitted when frequency of radiation is above a cutoff frequency f_c
It should take time for the electrons to absorb enough energy to be emitted (seconds)	First emitted electrons appear almost immediately (< 1 ns)

Photoelectric Effect

Light travels in "chunks" of energy called photons. The energy of a photon is determined by its frequency.

Energy of a photon

$E = hf \qquad h = 6.626 \times 10^{-34}$ J s

Momentum of a photon

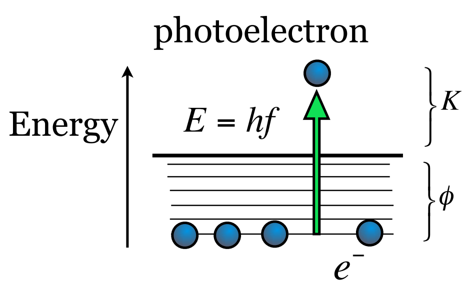
$$p = \frac{h}{\lambda}$$

Photoelectric formula

$$K_{max} = hf - \phi$$

$\phi =$ work function of the metal

$$f_c = \frac{\phi}{h} \quad = \text{cutoff frequency}$$



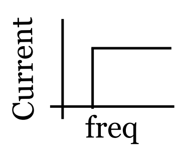
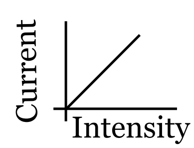
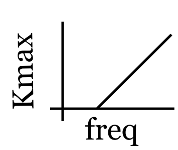
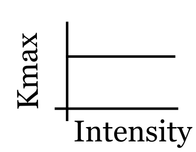
Photoelectric Effect - Experimental Results

Vary (columns) / **Measure** (rows)

	frequency	Intensity
Current of photoelectrons		
Max K.E. of photoelectrons		

Photoelectric Effect - Experimental Results

Vary (columns) / **Measure** (rows)

	frequency	Intensity
Current of photoelectrons		
Max K.E. of photoelectrons		

Question 1

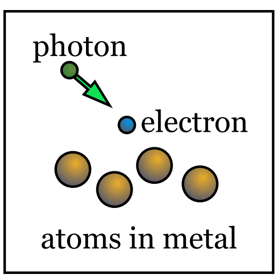
A source of light of wavelength λ is incident on a metal surface, and electrons of maximum kinetic energy *K* are observed to be emitted from the surface. The source is replaced by a different source that emits the same power (in watts) but has a smaller wavelength. Does the rate at which electrons are emitted from the surface *increase, decrease, or remain the same*, and does their maximum kinetic energy *increase, decrease, or remain the same?* EXPLAIN YOUR ANSWER

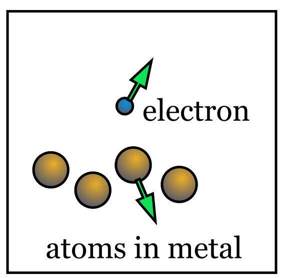
Problem 1

Light of wavelength 435 nm is incident on a metal surface, and it is observed that electrons leave the surface with a maximum kinetic energy of 1.16 eV.
(a) What is the work function of this metal?
(b) What is the maximum kinetic energy of the electrons if light of wavelength 560 nm is used?
(c) What is the longest wavelength of light that will cause electrons to be emitted from this surface?

Photoelectric Effect

photon + electron → electron



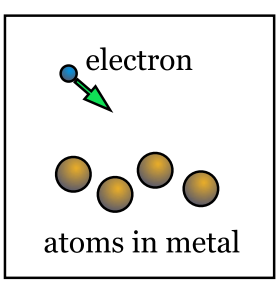


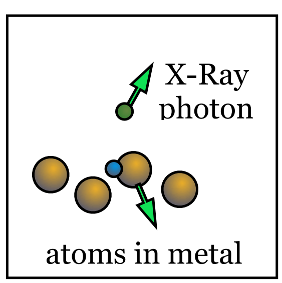
$$K_{max} = hf - \phi$$

$$E = hf$$

X-Ray Production (Bremsstrahlung Radiation)

electron → electron + photon

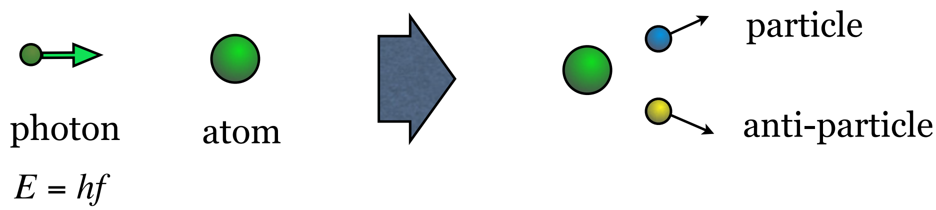




$$\lambda_{min} = \frac{hc}{K}$$

Pair Production: photon turns into particle + antiparticle

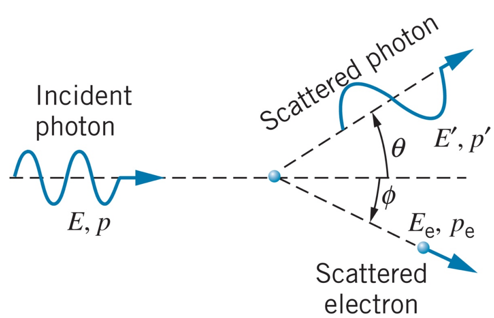
Photon gives up all its energy to create a particle/anti-particle pair.



$$\sum m_{new}c^2 = hf - K.E.$$

Compton Effect: photon scatters off electron

photon + electron → photon + electron

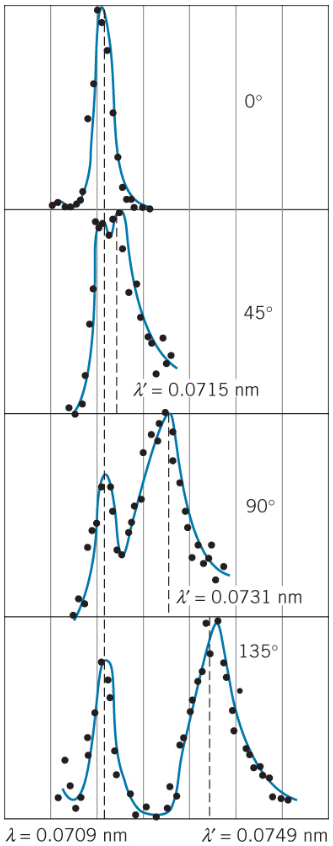


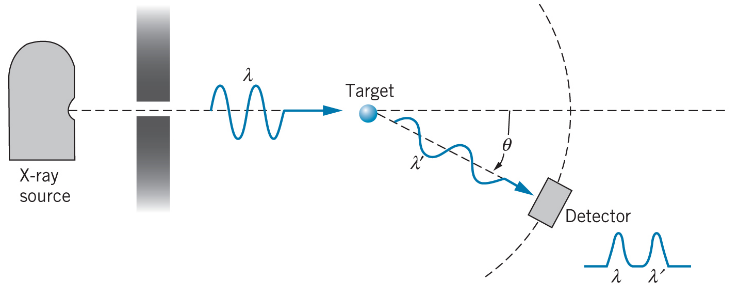
$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

Classical Prediction: scattered radiation has less energy but same wavelength as incident radiation

Quantum Prediction: scattered radiation has less energy and longer wavelength than incident radiation

Compton Effect





$$\lambda' - \lambda = \frac{h}{m_e c}\left(1 - \cos\theta\right)$$