Purdue University Department of Physics

Physics 21900

General Physics II

Electricity, Magnetism and Optics

Lecture 24 – Chapter 26.1-4

Quantum Optics: Photons

Fall 2015 Semester

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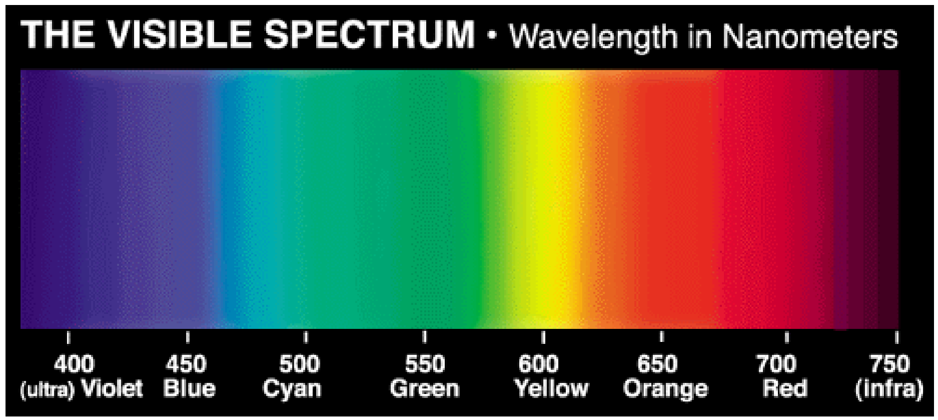
Useful Concepts

- Wavelength, λ, describes the "color" of light:



- We use the intensity (power per unit area) to describe the "amount" of light.
- We can talk about the *power per unit wavelength* to describe the amount of light of a particular color (the *spectrum*).

Blackbody Radiation

- Hot objects radiate electromagnetic radiation.
- Very hot objects emit enough light in the visible range that you can see them glow.
- We can feel heat (infrared radiation) even though we can't see it.

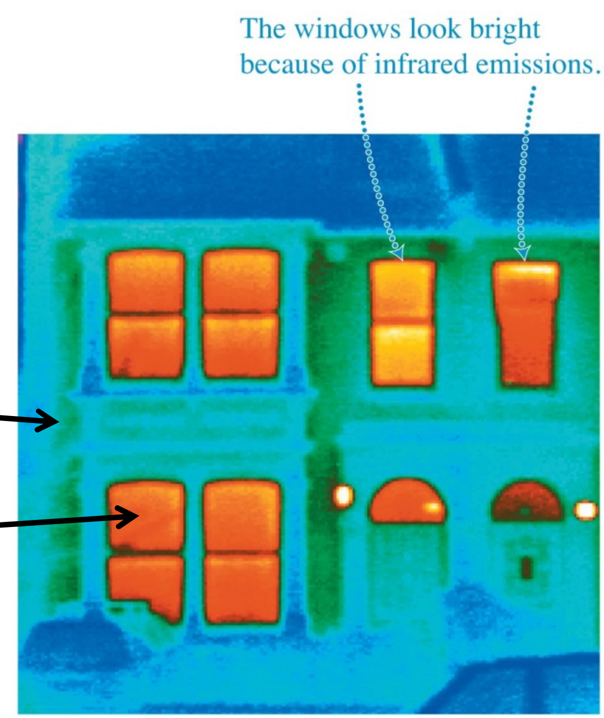
Blackbody Radiation

- A “blackbody” is an idealized situation where an object absorbs all incident light (no reflection).
- A blackbody radiates electromagnetic waves based solely on its temperature.

Infrared camera showing radiated heat from a building.

The outside walls are cold, so they show up as blue.

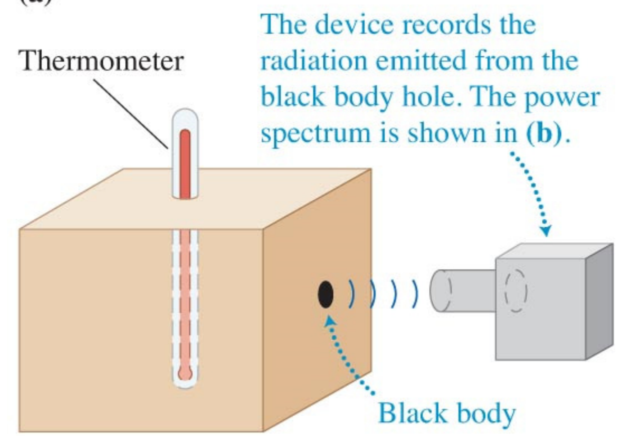
The inside is hot and the radiated heat shows up as orange.



Blackbody Radiation

- A blackbody can be modeled by a small hole in the side of a closed container.
  - All light passing through the hole gets trapped inside
  - The heat inside the container radiates out the hole
- The power spectrum is a graph of the intensity as a function of wavelength.
  - Total power is the area under the whole curve
  - The "color" depends on the peak position.

(a)



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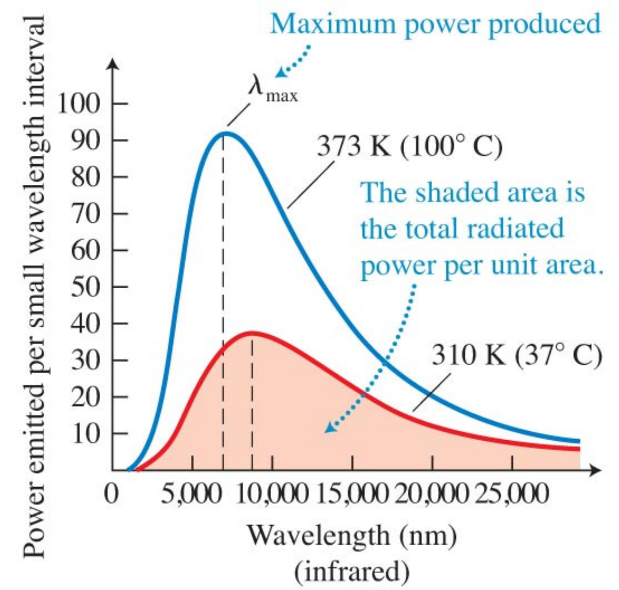
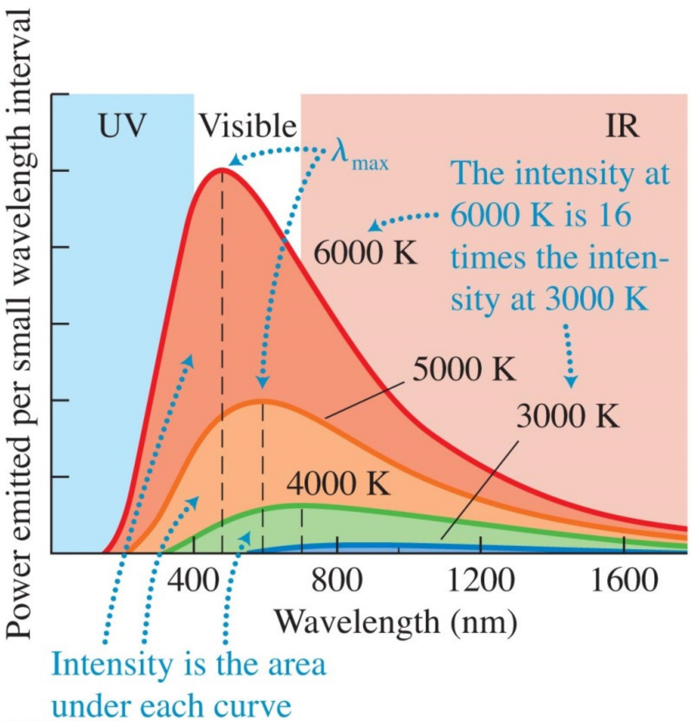


Blackbody Radiation

- If we increase the temperature, we notice three things:
  1. The total power output from the hole is now greater.
  2. The intensity increases at all wavelengths
  3. The position of the peak intensity shifts towards smaller



Stephen's Law:

$$P = \varepsilon A = \sigma T^4 A$$

The power radiated is proportional to T^4.

$$\boldsymbol{\sigma = 5.67 \times 10^{-8}\, W \cdot m^{-2} \cdot K^{-4}}$$

is just a constant of proportionality.

Blackbody Radiation

TIP A black body (the system) emits electromagnetic waves with power given by Stefan's law even if it is at the same temperature as the environment—but it also absorbs energy at the same rate. If the body is hotter than the environment, it radiates more energy than it absorbs. If it is cooler, it absorbs more than it radiates. Emission or absorption continues until the black body reaches thermal equilibrium with the environment.

Blackbody Radiation

- In 1893, the German physicist Wilhelm Wien (1864–1928) quantified a second aspect of black body radiation.
- He defined a relationship for the maximum wavelength at which a black body emits radiation of maximum power per wavelength:

$$\lambda_{max} = \frac{2.90 \times 10^{-3}\,\mathrm{m \cdot K}}{T}$$

The wavelength at which the intensity is maximum is inversely proportional to the temperature.

Example

- The maximum power per wavelength of light from the Sun is at a wavelength of about 510 nm, which corresponds to yellow light. What is the surface temperature of the Sun?
- Wein's displacement law:

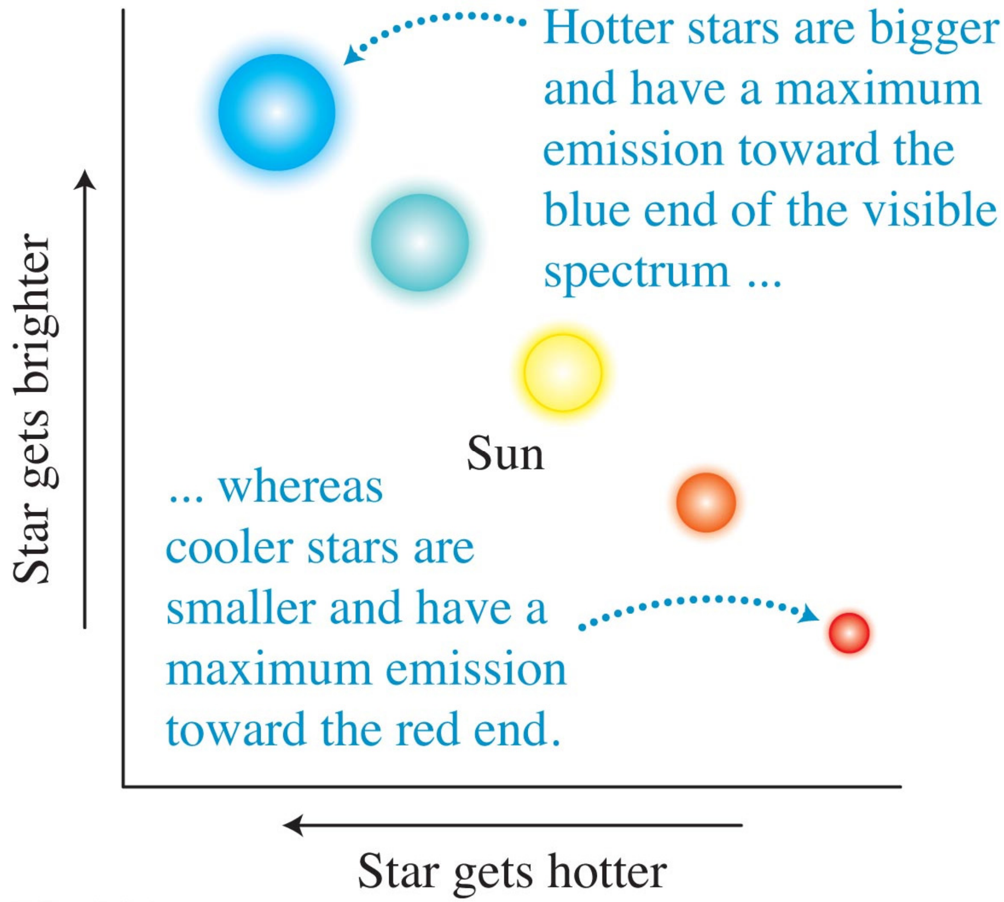
$$\lambda_{max} = \frac{2.90 \times 10^{-3}\ m \cdot K}{T}$$

$$T = \frac{2.90 \times 10^{-3}\ m \cdot K}{\lambda_{max}} = \frac{2.90 \times 10^{-3}\ m \cdot K}{510 \times 10^{-9}\ m}$$

$$= 5686\ K$$

The color of stars

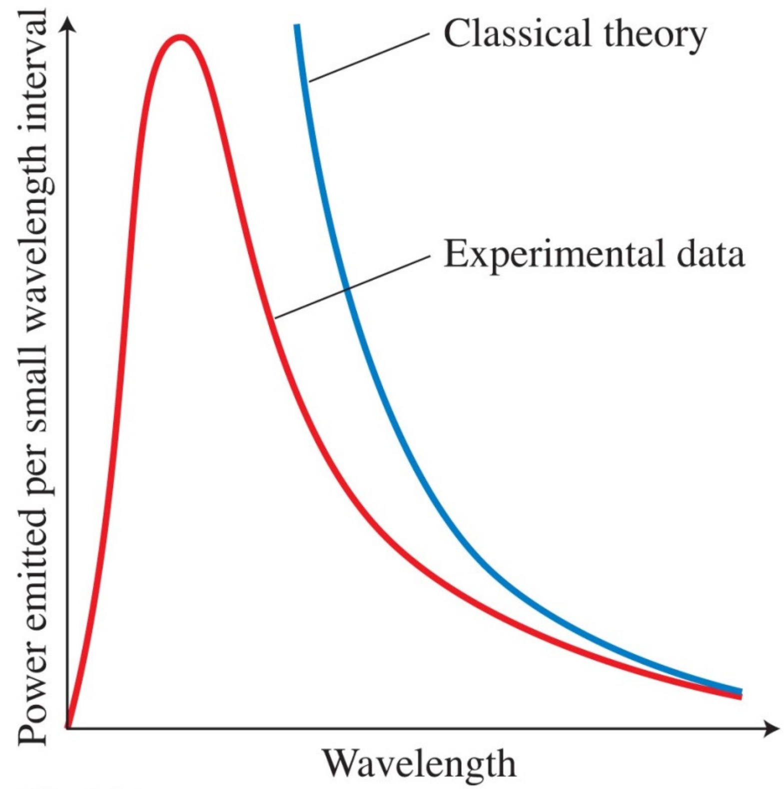
- Very hot stars (around 10,000 K) look blue.
- Even hotter stars are generally invisible to our eyes.



The "ultraviolet catastrophe"

- In the late 19th century, no models could explain why the intensity dropped at small wavelengths.

This problem became known as the "ultraviolet catastrophe".



Planck's Quantum Hypothesis

- Planck hypothesized that charged particles could only emit light in discrete portions called "quanta".
- According to Planck, a particle could emit amounts of energy equal only to multiples of a fundamental portion.
- In classical physics, the frequencies of a wave in a box are quantized.
  - The energy of these waves can take on any value because the energy of the wave depends on its amplitude and not its frequency.
- In quantum physics, the energy of the oscillator is quantized, rather than its frequency.

Planck’s Hypothesis

- Using his energy quantization model, Planck derived a relation between the energy and the frequency of a quanta of electromagnetic radiation:

$$E_0 = hf$$

- The constant, h, became known as Planck’s constant.

$$h = 6.626 \times 10^{-34}\, J \cdot s$$

- The energy of light emitted with frequency f can only be

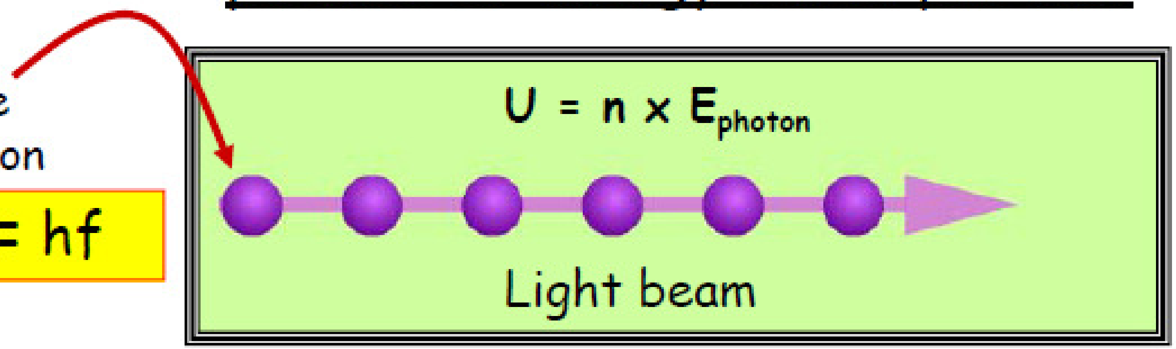
$$E = n\, E_0$$

where n is an integer. When n is large enough, the spectrum of possible energies is almost continuous.

Planck's idea (in 1900) followed up by Einstein (in 1905) who hypothesized that light sometimes behaves like quantized packets of energy called photons

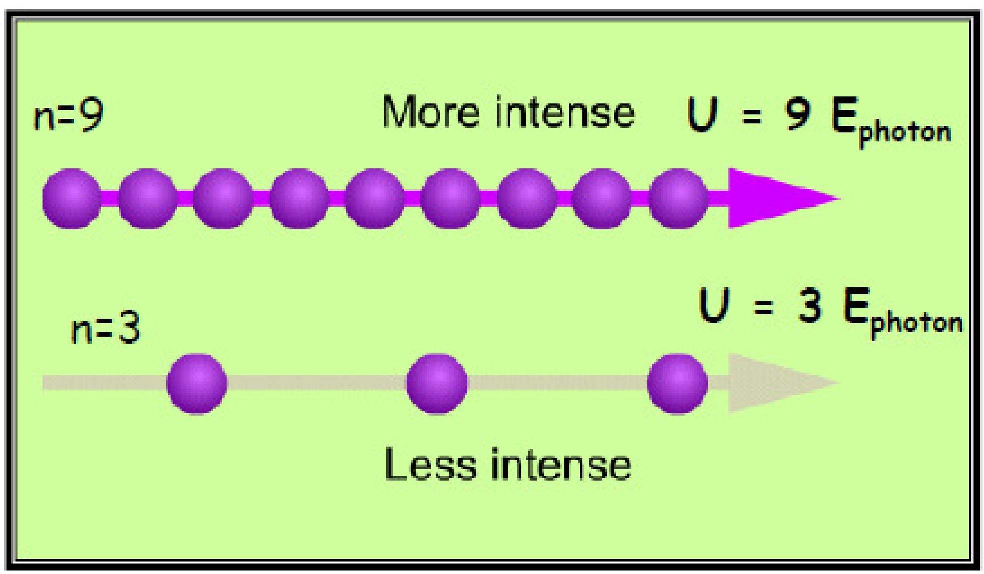
one photon

$E_{photon} = hf$



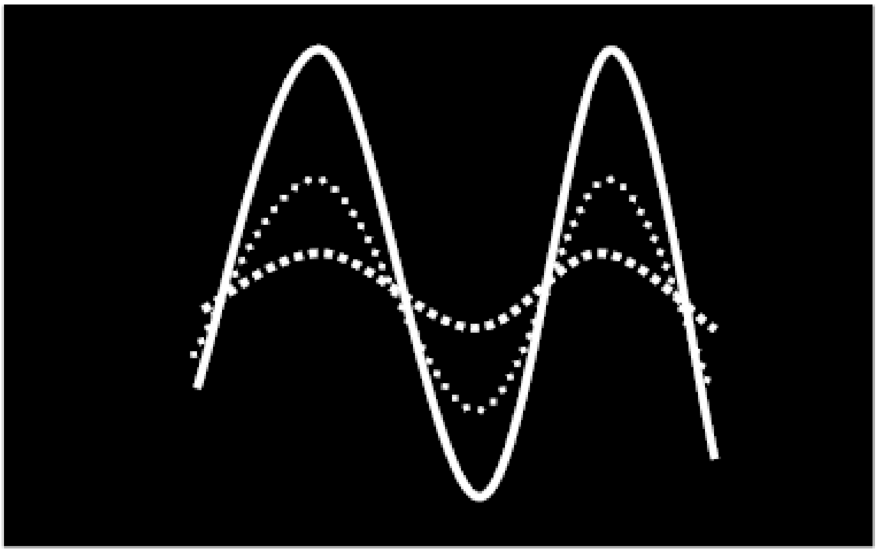
U is energy in light beam

Examples:



Foundation of QUANTUM optics

Why is the quantization hypothesis so surprising?



for EM plane wave

$$\vec{S} = \frac{1}{\mu_o}\vec{E}\times\vec{B}$$

$$I \equiv \left|\vec{S}\right|_{AVERAGE} = \frac{1}{2}c\varepsilon_o E_o^2 = c\varepsilon_o E_{rms}^2$$

Since light is a wave (only way to explain interference and diffraction effects from the early 1800's), **everyone** thought that it's energy could be varied **continuously** by adjusting the wave's E-field amplitude.

This simple idea was completely contradicted by Planck's hypothesis.

Photons and the Photoelectric Effect

- If the energy of light with frequency f is quantized, can we detect the smallest possible quanta of light (a photon)?
- A photon incident on a metal can eject an electron.
  - Some of the photon's energy is used to remove the electron from the surface of the metal
  - The rest of the photon's energy goes into the electron's kinetic energy
- It is convenient to measure small energies using "electron-volts":

$$\mathbf{1\ eV = 1.602 \times 10^{-19}\ J}$$

(The change in an electron's energy after moving across a potential difference of one volt.)

Work Function

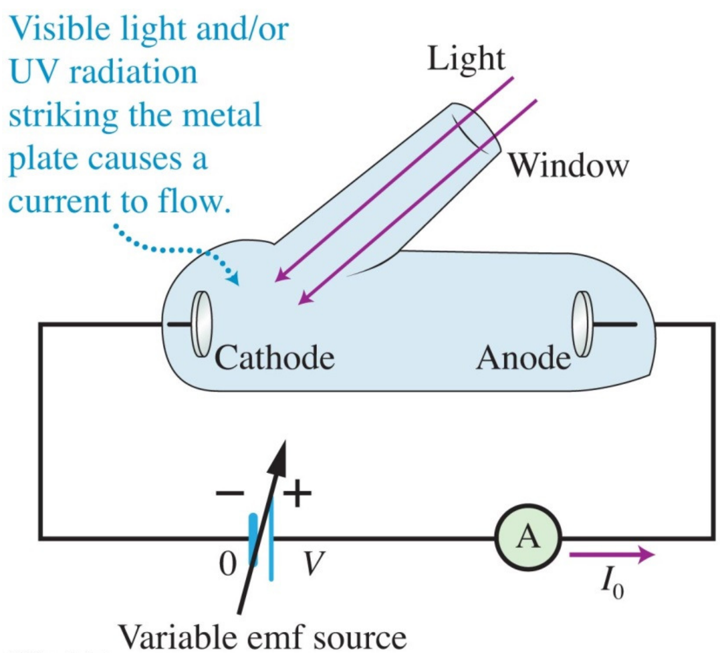
- The work function is the minimum energy needed to remove a free electron from a metal.
  - The work function has units of energy but is measured in electron volts because it is typically very small.
  - The greater the work function of a metal, the more tightly the free electrons are bound to the metal and the more energy must be added to separate them.

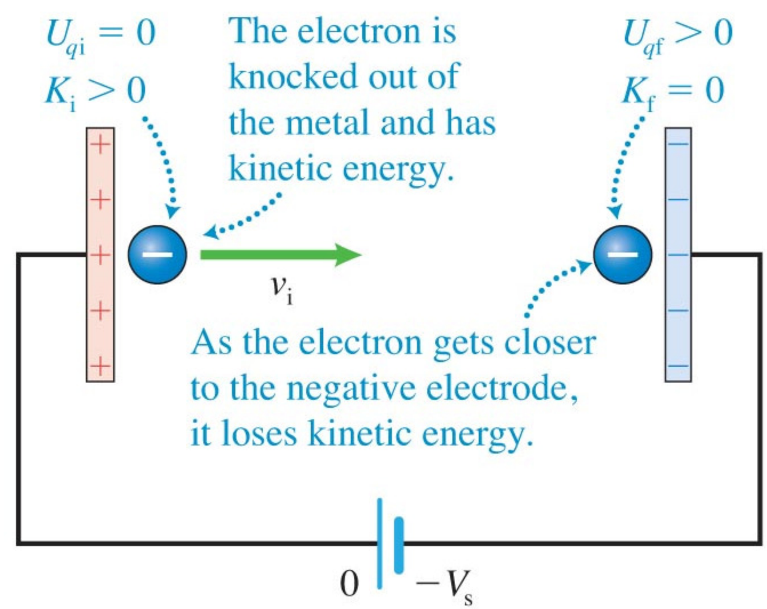
Work Function

TIP Even though ϕ is called the work "function," it's not a function in the mathematical sense. It is a constant that differs from material to material. And although some electrons in metals are called "free" electrons, they are not free to leave the metal; they are free to move around within the metal, however.

Photoelectric Effect

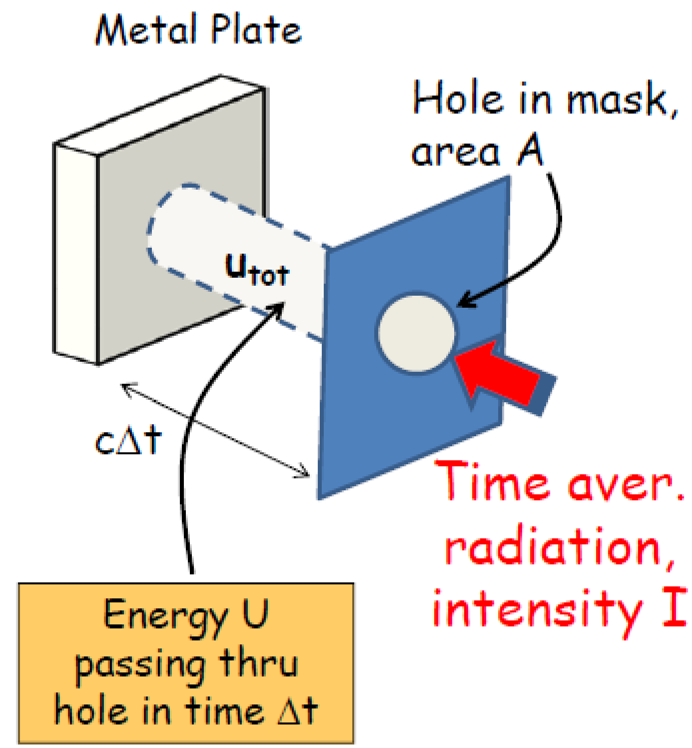
- If a metal has a work function ϕ then a photon with energy $E = hf < \phi$ will not have enough energy to remove an electron from the surface.
- No current will flow if the electron does not have enough energy to overcome the potential difference V.





Photoelectric Effect

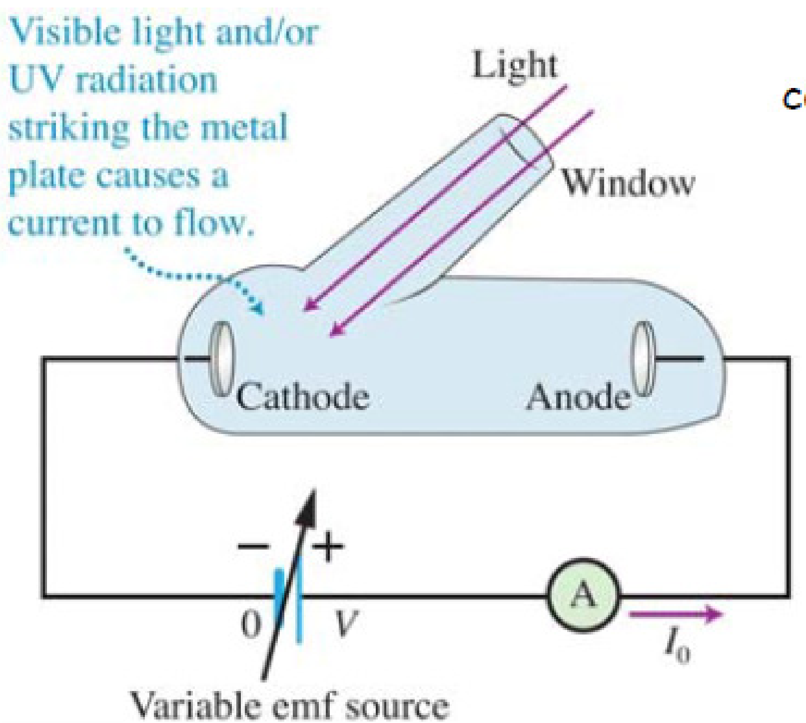
- Classical explanation:
  - As the intensity is increased, the maximum energy of the ejected electrons should also increase.
    $U = P\Delta t = (I \times A)\Delta t$
  - At low enough intensities, there will be a delay in electron emission
  - It takes time for the electrons to absorb enough energy to be emitted
  - Electrons should be emitted for all wavelengths of light.

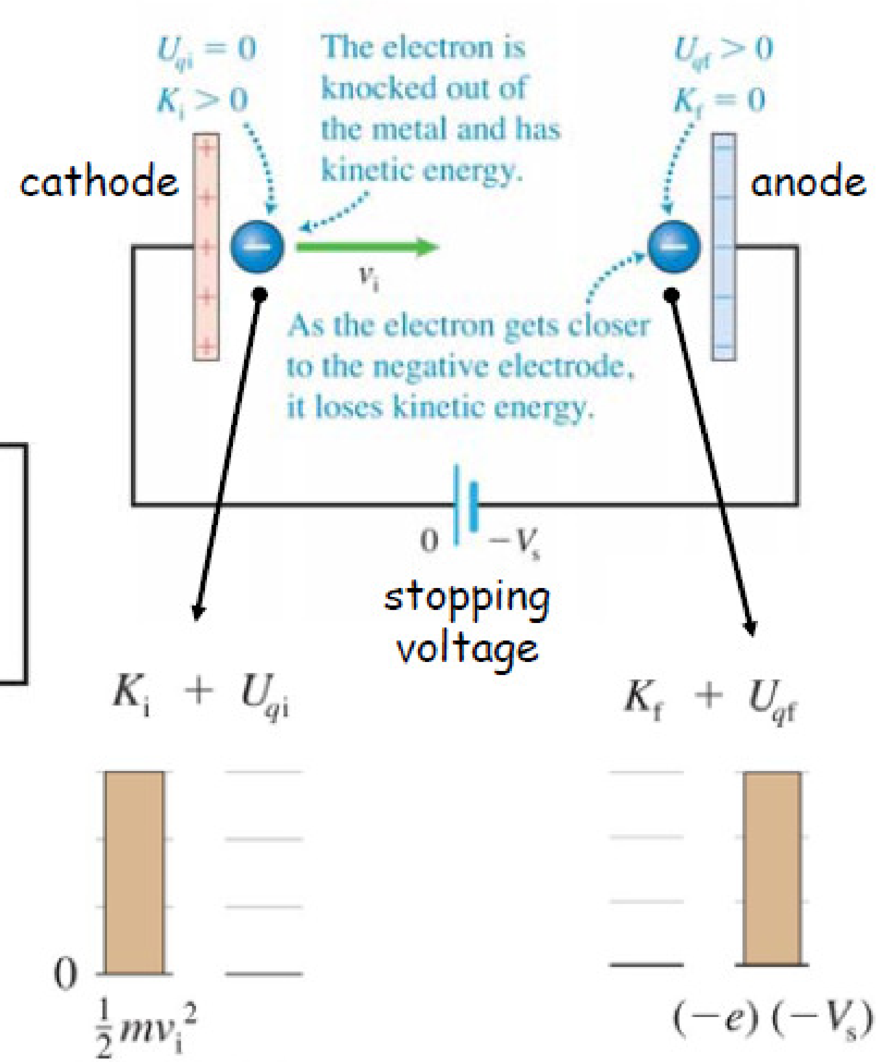


Photoelectric Effect

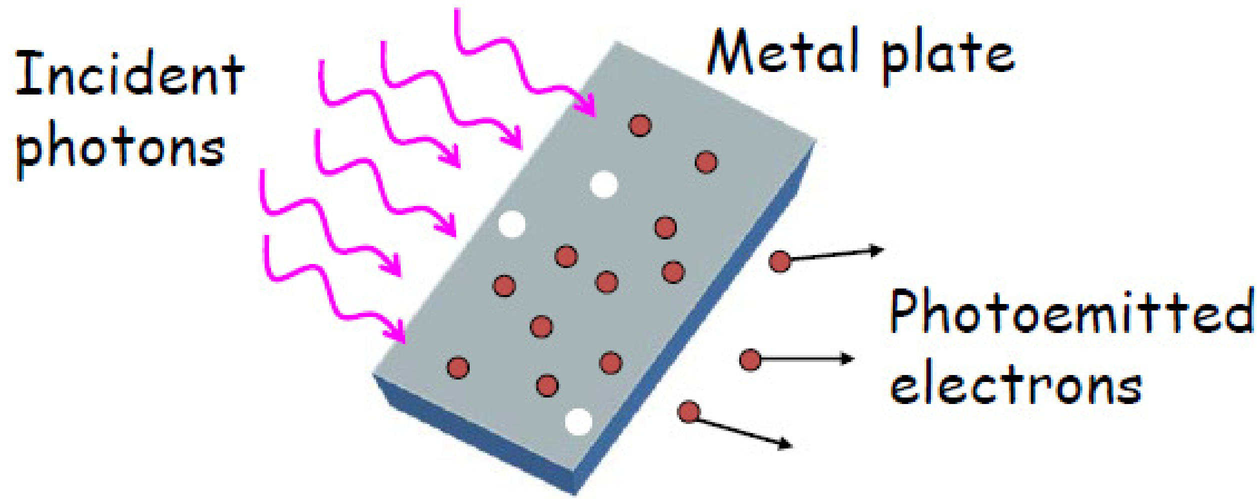
- Long wavelengths (eg, red light) did not eject any electrons, independent of the intensity.
- Blue light did cause a current to flow
- The voltage needed to stop the current flow depended on the wavelength
  - This measures the maximum kinetic energy of the electrons when ejected from the surface of the metal
- The current depended on the intensity

Experimental Details





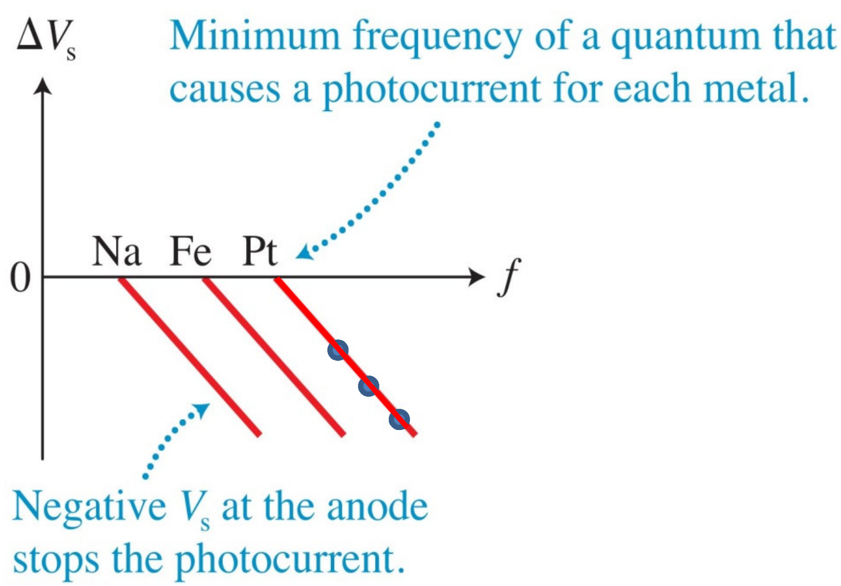
Einstein's Theory of Photoemission



Individual photons interact with individual electrons to cause an electron to be ejected. There is a threshold energy for electron ejection (the work function) due to the atomic composition of the target plate.

Example

- Light and UV radiation shine on three different metals. Graph lines representing the stopping potential versus the incident light or UV frequency are shown below. The work functions of the metals are sodium (Na), 2.3 eV; iron (Fe), 4.7 eV; and platinum (Pt), 6.4 eV. Use Einstein's hypothesis of light absorption to explain the results.



Typical questions

Calculate the energy (in eV) of a photon of blue light with λ = 400 nm

$$E_{photon} = hf = h\frac{c}{\lambda} = 3.1\,eV$$

If this photon strikes a metal plate having a work function of 2.2 eV, is it possible that an electron will be emitted?

Yes, because $E_{photon} > \Phi$

What will be the maximum kinetic energy of an electron ejected from the metal plate when these blue photons strike it?

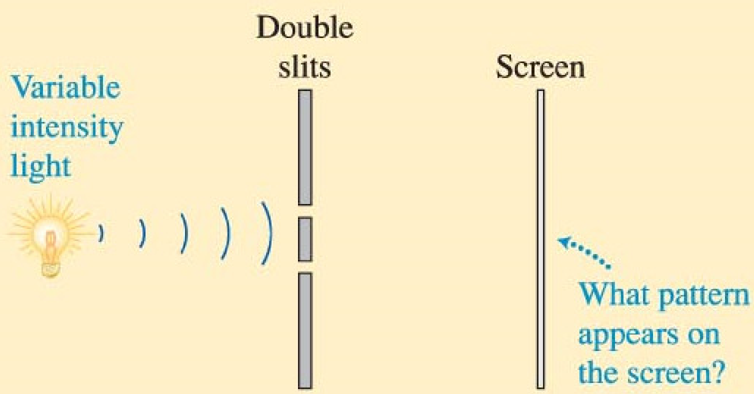
$$E_{kin} = E_{photon} - \Phi = 3.1 - 2.2 = 0.9eV$$

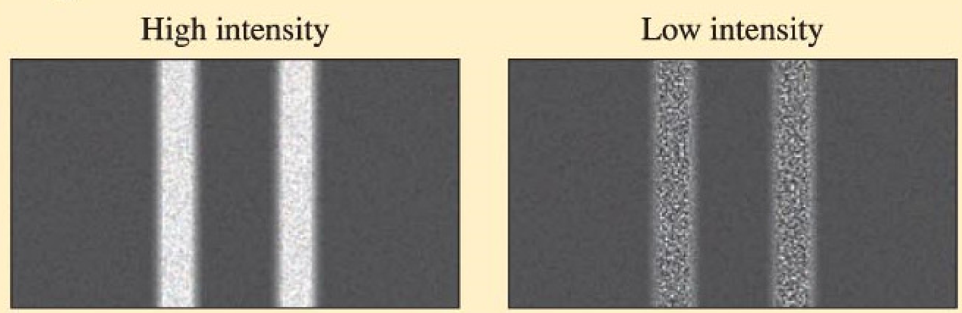
Photons

- Physicists started to think of light as being composed of particle-like photons (the quanta of light).
- To explain interference and diffraction phenomena, the photons also had to have wave-like properties.
- This is called the dual particle-wave property of photons.
- Can we observe this directly?

Double Slit Experiment

Testing experiment	Prediction
Use a light source with variable intensity. Shine the light on two narrow slits. Place a fluorescent screen beyond the slits that indicates where light hits the screen.	*Particle model:* Only two bright bands should appear—images of the slits themselves. As intensity decreases, we expect to see individual flashes caused by single photons at the slit image locations.





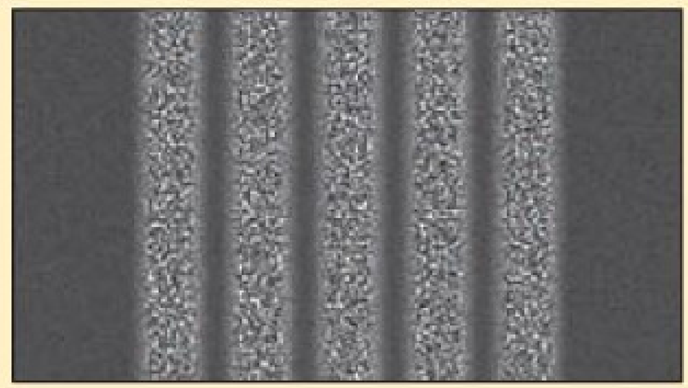
If photons were classical particles, then they would pass through one slit or the other slit, one at a time. At very low intensities, there should be no wave-like interference.

"Wave-Particle Duality"

Dual wave-particle (photon) model: Many alternating bright and dark bands should appear. As the intensity decreases, we expect to see individual flashes due to single photons at bright band locations only. At the locations of the dark bands no flashes should be seen.

High intensity

Low intensity



At low intensities, even though photons can be counted and carry quantized energy, they behave like waves, passing through both slits and causing interference effects.