Chapter 31

Light Quanta

Quantization of Light

Recall from previous chapter that "light has particle-like behavior." A "quantum" of light is called a *photon*.

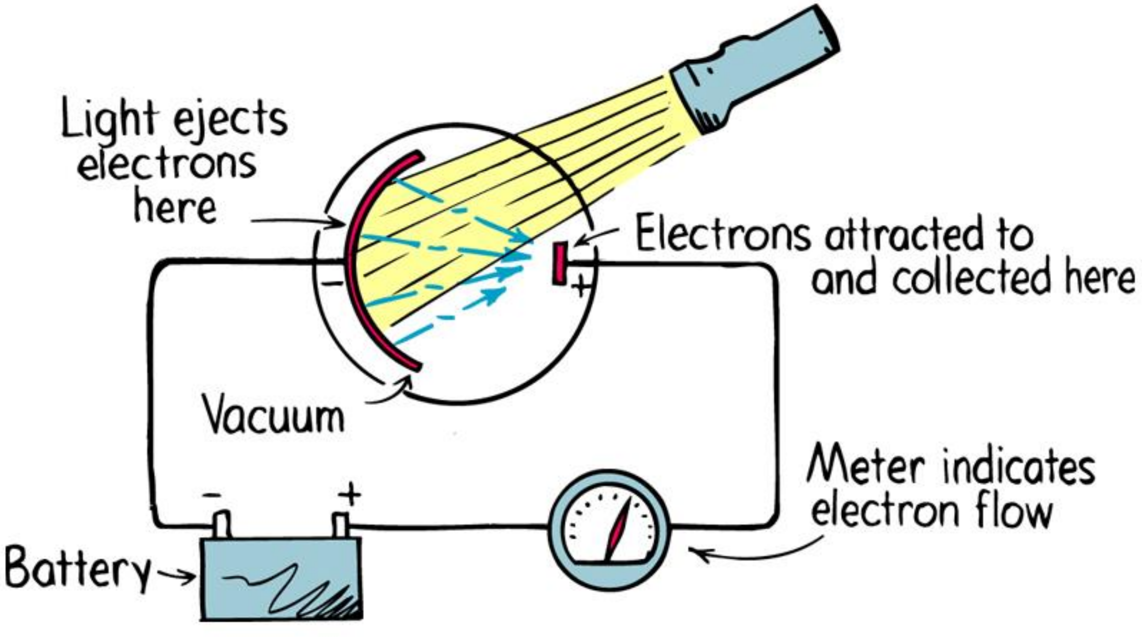
The energy of a single photon of light having a frequency f is given by

$E = hf$, where h = Planck's constant = 6.626×10^{-34} J-s.

A monochromatic beam of light containing n photons has a total energy, $E = nhf$.

Photoelectric Effect

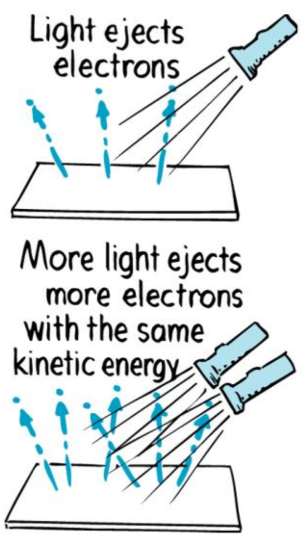
Light of certain frequencies can eject electrons from the surfaces of metals.

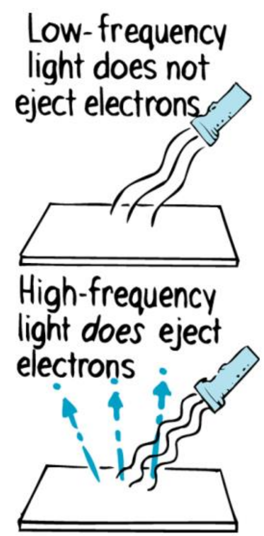


Photoelectric Effect: Odd Findings

Higher intensity light does NOT increase the energy of the ejected electrons—it just ejects more of them.

Below a threshold frequency, no electrons are ejected no matter how intense the light is.





Einstein to the Rescue (again!)

- Einstein: The photoelectric effect can be easily explained if one assumes that the light behaves like a stream of particles (photons).
- A certain amount of energy is required to eject an electron from the metal. Only photons having sufficient energy (higher enough frequency) will eject electrons. If the energy of the photons is too low, no electron will be ejected no matter how bright (intense) the light is.
- Each photon ejects one electron. That is why brighter light ejects more electrons of the same energy rather than the same number of electrons with greater energy.
- Punchline: The photoelectric effect demonstrates the particle nature of light.

Particles as Waves

Louis de Broglie's hypothesis:

If light (which we thought was a wave) can behave like a particle, can an electron (which we though is a particle) behave like a wave? YES!

Wavelength = Planck's constant / Momentum

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

Electron diffraction demonstrates this!

Example #1

Calculate the de Broglie wavelength of a 90 mph fastball. The mass of a baseball is about 0.15 kg.

Converting 90 mi/hr (try this yourself!) you should get about 40 m/s. Then plug numbers into formula:

$$\lambda = \frac{6.626 \times 10^{-34}\text{Js}}{(0.15\text{ kg})(40\text{ m/s})} = 1.1 \times 10^{-34}\text{m}$$

This result is about 19 powers of ten smaller than the diameter of an atomic nucleus!

Bottom line: We do not observe the wave-like properties of every macroscopic objects.

Example #2

Calculate the de Broglie wavelength of an electron moving 1% times the speed of light. Look up the necessary

Converting 90 mi/hr (try this yourself!) you should get about 40 m/s. Then plug numbers into formula:

$$\lambda = \frac{6.626 \times 10^{-34}\text{Js}}{(9.11 \times 10^{-31}\text{ kg})(3.0 \times 10^{6}\text{ m/s})} = 2.4 \times 10^{-10}\text{m}$$

This result is about the size of an atom. This should not be surprising. The size of an atom is determined by the electron cloud surrounding the

Bottom line: The "smearing out" of the electron wave is what gives the atom its overall size.

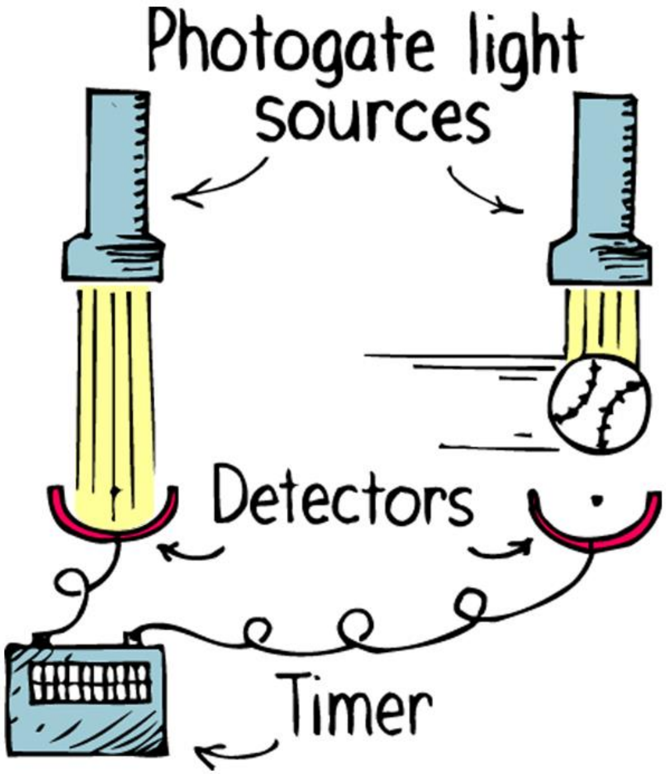
The Uncertainty Principle

Puts a limit on how well the position and momentum of a particle can be simultaneously measured.

$$\Delta x \Delta p > h/2\pi$$

where Δx is the uncertainty is the position ($x_{max} - x_{min}$), and Δp is the uncertainty in the momentum ($p_{max} - p_{min}$).

The better you know the position, the less you know about the momentum of the particle.



The Uncertainty Principle

The uncertainty principle also puts a limit on how well the energy of an particle can be measured within a time interval.

$$\Delta E \Delta t > h/2\pi$$

Since *h* is so small, we do don worry about the quantum uncertainties of a baseball.

Quantum uncertainties are only prevalent in the microscopic realm.

Complementarity

Both the wave-like and particle-like aspects of light and matter are necessary for a complete description.

We observe the wave-like aspects when we probe wave-like properties (interference, diffraction, polarization) and we observe particle-like aspects when we probe particle-like behavior (such as the photoelectric effect. We can conclude that…

light travels through space like a wave and interacts with matter like a particle.