Chemistry 1000 Lecture 5: Light

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A bit of history

Two dominant theories on the nature of light, going back to ancient times:

Corpuscular (particle) theory: Explains some observations, like the straight-line propagation of light rays

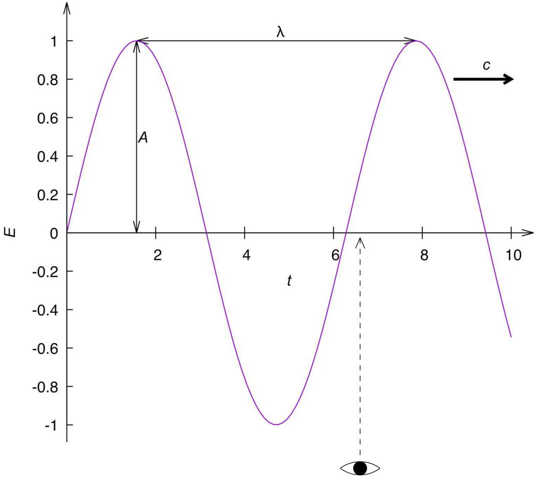
- The Indian Vaisheshika philosophical school (6th–5th century BC) held that light is made of atoms of fire.
- Alhacen's *Book of Optics* (1021) hypothesized that light is made of particles emitted by illuminated objects.
- Newton's *Opticks* (1704) contained a detailed corpuscular theory.

Wave theory: Explained most properties of light

- Hooke (1665) and Huygens (1690) both presented wave theories of light.
- Faraday (1847) proposed that light is an electromagnetic wave.
- Maxwell (1862) showed that electromagnetic theory predicted waves.

Triumph of Maxwell's theory: Discovery of radio waves by Hertz (1886–87)

Wave properties



$$\nu = \frac{\text{\# waves (cycles)}}{\text{time}}$$

Frequency-wavelength relationship for light

$$\boxed{c = \lambda\nu}$$

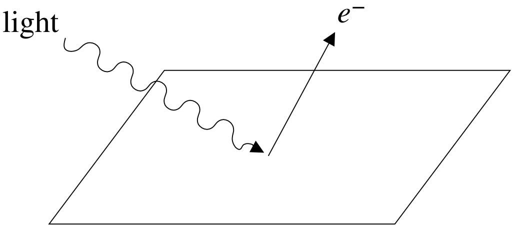
c is the speed of light in m/s.

$$c = 2.997\,924\,58 \times 10^8 \text{ m/s} \qquad \text{(by definition)}$$

λ is the wavelength in m.

ν is the frequency in Hz (cycles per second).

Photoelectric effect

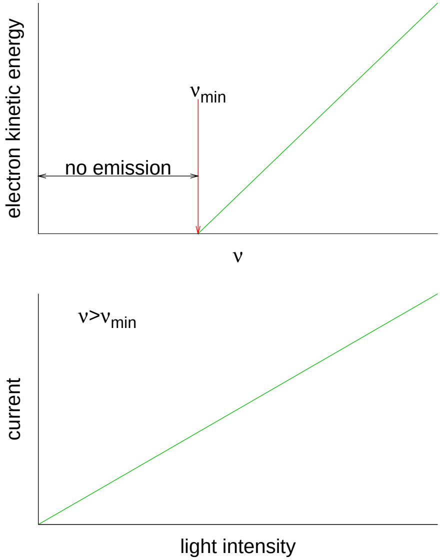


According to classical physics the energy carried by a wave depends on the square of its amplitude.

For light, amplitude = intensity.

Prediction: Not enough energy to remove electrons?
Increase the intensity of the light.

Observations:



Einstein's solution

- Light is made of particles called photons.
- Photons obey Planck's equation

$$\boxed{E = h\nu}$$

E is the energy of one photon in J.
h is Planck's constant in J/Hz
(sometimes written J s).

$$h = 6.626\,070\,15 \times 10^{-34}\ \text{J/Hz}$$

(Fixed value to be adopted in the new SI system)

Duality: Light is *both* a particle *and* a wave!

- Photochemical equivalence: Matter interacts with photons one by one, i.e. each photon is responsible for the ejection of *one* electron.

$$\begin{aligned}\text{electron k.e.} &= \text{energy supplied} - \text{energy to remove electron}\\ eV_s &= h\nu - e\phi\\ V_s &= \frac{h}{e}\nu - \phi\end{aligned}$$

$\Longrightarrow$ Slope of plot of stopping potential V_s vs $\nu = \dfrac{h}{e}$

1921 Physics Nobel Prize

To Albert Einstein, for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect

http://nobelprize.org/nobel_prizes/physics/laureates/1921

Photons vs waves

- $c = \lambda\nu$ (because light is a wave) and $E = h\nu$ (from Einstein)
- Combine the two to get
$$E = \frac{hc}{\lambda}$$

Momentum-wavelength relationship for photons

- In classical mechanics, momentum is a conserved "amount of motion" calculated by

$$p = mv$$

- From Einstein's relativity theory, we have

$$E^2 = c^2p^2 + m_0^2c^4$$

- Photons are massless, so $m_0 = 0$, which gives $E = cp$.
- Since E is also equal to hc/λ, we get

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

Example: Calculations of wave/photon properties

Fluorescent light contains a strong green line with a wavelength of 546 nm. From the wavelength, we can calculate the following:

$$\nu = \frac{c}{\lambda} = \frac{2.997\,924\,58 \times 10^{8}\,\text{m/s}}{546 \times 10^{-9}\,\text{m}} = 5.49 \times 10^{14}\,\text{Hz}$$

$$E = h\nu = (6.626\,069\,57 \times 10^{-34}\,\text{J/Hz})(5.49 \times 10^{14}\,\text{Hz})$$
$$= 3.64 \times 10^{-19}\,\text{J}$$

$$p = \frac{h}{\lambda} = \frac{6.626\,069\,57 \times 10^{-34}\,\text{J/Hz}}{546 \times 10^{-9}\,\text{m}} = 1.21 \times 10^{-27}\,\text{kg m/s}$$

$$E_m = N_A\,E = (6.022\,141\,99 \times 10^{23}\,\text{mol}^{-1})(3.64 \times 10^{-19}\,\text{J})$$
$$= 219\,\text{kJ/mol}$$

$$p_m = N_A\,p = (6.022\,141\,99 \times 10^{23}\,\text{mol}^{-1})(1.21 \times 10^{-27}\,\text{kg m/s})$$
$$= 7.31 \times 10^{-4}\,\text{kg m s}^{-1}\text{mol}^{-1}$$

Electromagnetic spectrum

- From shortest to longest wavelength (highest to lowest energy): gamma rays, X rays, ultraviolet, visible, infrared, microwave, radio
- Visible range: 400–760 nm
  - From shortest to longest wavelength (highest to lowest energy): violet, blue, green, yellow, orange, red
- Memorize content of this slide.

Some typical numbers

Source	λ	ν	E_m
CKXU 88.3 FM:	3.40 m	88.3 MHz	35.2 mJ/mol
Microwave oven:	12.2 cm	2.45 GHz	0.978 J/mol
Green light:	546 nm	549 THz	219 kJ/mol
Near UV:	300 nm	1 PHz	400 kJ/mol
Far UV:	100 nm	3 PHz	1 MJ/mol
Medical diagnostic X-rays:	31 pm	10 EHz	4 GJ/mol