L13 – Photons

$c = 3.0 \times 10^8 \, m/s$
$\lambda = $ wavelength
$f = $ freq

Atomic Physics

$W = hf_0$

$E = hf = \dfrac{hc}{\lambda}$

$E_{k_{max}} = q_e V_{stop}$

$N = N_0 \left(\dfrac{1}{2}\right)^n$

Momentum and Energy

$\vec{p} = m\vec{v}$

$E_k = \dfrac{1}{2}mv^2$

$\vec{F}\Delta t = m\Delta\vec{v}$

$E_p = mgh$

$W = |\vec{F}||\vec{d}|\cos\theta$

$E_p = \dfrac{1}{2}kx^2$

$W = \Delta E$

$P = \dfrac{W}{t}$

Waves

$T = 2\pi\sqrt{\dfrac{m}{k}}$
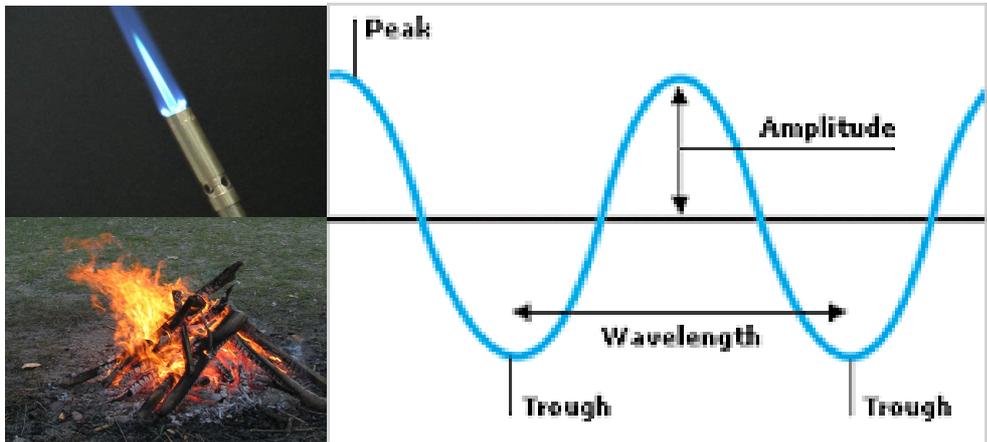
$m = \dfrac{h_i}{h_o} = \dfrac{-d_i}{d_o}$

$T = 2\pi\sqrt{\dfrac{l}{g}}$

$\dfrac{1}{f} = \dfrac{1}{d_o} + \dfrac{1}{d_i}$

$T = \dfrac{1}{f}$

$\dfrac{\sin\theta_1}{\sin\theta_2} = \dfrac{n_2}{n_1} = \dfrac{v_1}{v_2} = \dfrac{\lambda_1}{\lambda_2}$

$v = f\lambda$

$\lambda = \dfrac{d\sin\theta}{n}$

$f = \left(\dfrac{v}{v \pm v_s}\right)f_s$

$\lambda = \dfrac{xd}{nl}$

Energy of a Photon

Wave Properties	Particle Properties
- Interference	- Energy not related to Amplitude
- Diffraction	- i.e. White fire hotter than Red fire
- Reflection	

Temperature Graphs for Blackbody Radiators

Energy emitted from an opaque and non-reflective body held at a constant, uniform temperature.

1. Hot, glowing objects emit a continuous range of wavelengths and hence a continuous spectrum of colours.

2. For a given temperature, the light emitted by the object has a range of characteristic wavelengths, which determine the object's colour when it glows.

3. The hotter an object is, the bluer the light it emits. The cooler an object is, the redder its light is.
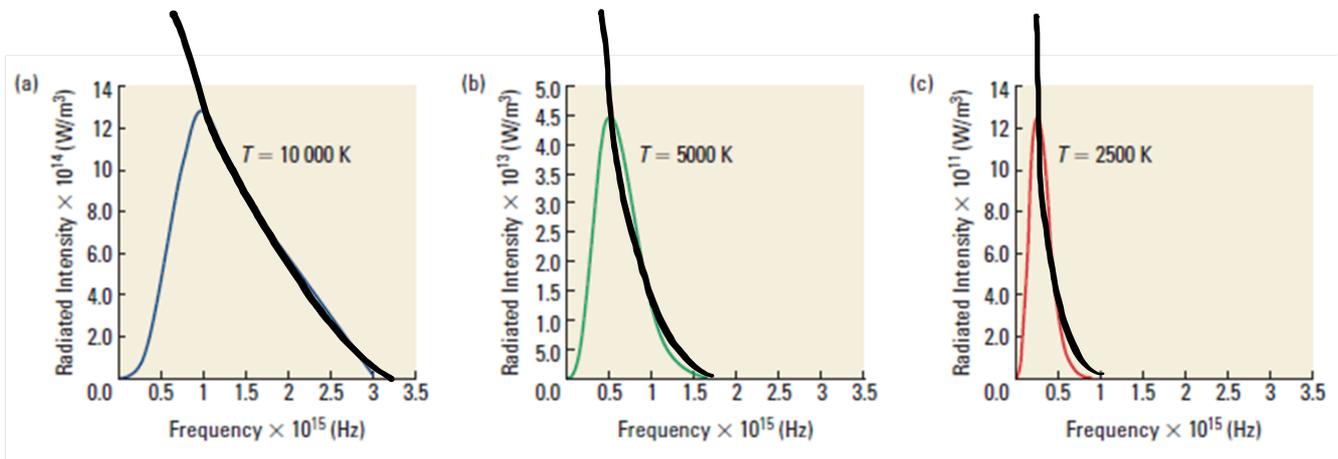
Photons as Energy Packets ("Particles")

Planck proposed that light traveled in packets of energy called photons.

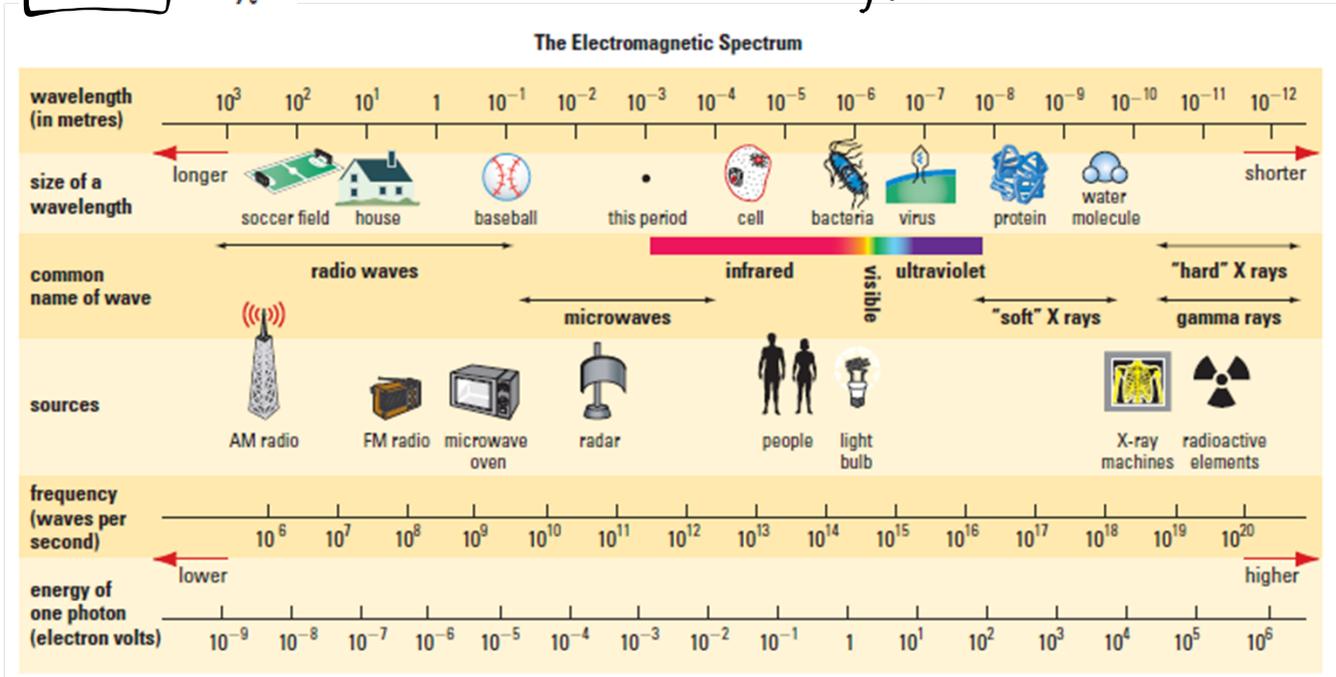$$\boxed{E \ = \ hf} = \frac{hc}{\lambda} \qquad \boxed{E = nhf}$$

Planck's Constant.............. $h = 6.63 \times 10^{-34}$ J·s
$h = 4.14 \times 10^{-15}$ eV·s

EMR Spectrum – Which has the highest energy?

Low f   High f

RMIVUXG

Low E   Higher E

$$E = hf = \frac{hc}{\lambda}$$

The Electromagnetic Spectrum

wavelength (in metres)	10^3	10^2	10^1	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10} 10^{-11} 10^{-12}

size of a wavelength — longer ← ... → shorter

soccer field · house · baseball · this period · cell · bacteria · virus · protein · water molecule

common name of wave: radio waves · microwaves · infrared · visible · ultraviolet · "soft" X rays · "hard" X rays · gamma rays

sources: AM radio · FM radio · microwave oven · radar · people · light bulb · X-ray machines · radioactive elements

frequency (waves per second)	10^6	10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	10^{17}	10^{18}	10^{19} 10^{20}

lower ← ... → higher

energy of one photon (electron volts)	10^{-9}	10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10^1	10^2	10^3	10^4 10^5 10^6

Q1: How much energy is carried by a photon of red light of wavelength 600 nm?

$$E = hf \quad \text{or} \quad E = \frac{hc}{\lambda}$$

h = Plank's constant

$$h = 6.63 \times 10^{-34} \text{ Js}$$
$$h = 4.14 \times 10^{-15} \text{ eVs}$$

$$E = \frac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{(600 \times 10^{-9})}$$

$$E = 3.315 \times 10^{-19} \text{ J} \times \frac{1 \text{ eV}}{1.60 \times 10^{-19} \text{ J}} = \boxed{2.07 \text{ eV}}$$

or

$$E = \frac{(4.14 \times 10^{-15})(3.0 \times 10^{8})}{(600 \times 10^{-9})} = \boxed{2.07 \text{ eV}}$$

Q2: Your eye can detect as few as 500 photons of light. The eye is most sensitive to light have a wavelength of 510 nm. What is the minimum amount of light energy that your eye can detect?

Single Photon

$$E = \frac{hc}{\lambda}$$

$$E = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{(510 \times 10^{-9})}$$

$$= 3.90 \times 10^{-19} \text{ J}$$

$$E_{TOTAL} = (500)(3.90 \times 10^{-19})$$

$$= 1.95 \times 10^{-16} \text{ J}$$

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Q3: How many photons are emitted each second by a laser pointer that has a power output of 0.400 mW if the average wavelength produced is 600 nm?

Atomic Physics		Waves	
$W = hf_0$	$E = hf = \dfrac{hc}{\lambda}$	$T = 2\pi\sqrt{\dfrac{m}{k}}$	$m = \dfrac{h_i}{h_o} = \dfrac{-d_i}{d_o}$
$E_{k_{max}} = q_e V_{stop}$	$N = N_0\left(\dfrac{1}{2}\right)^n$	$T = 2\pi\sqrt{\dfrac{l}{g}}$	$\dfrac{1}{f} = \dfrac{1}{d_o} + \dfrac{1}{d_i}$

Momentum and Energy			
		$T = \dfrac{1}{f}$	$\dfrac{\sin\theta_1}{\sin\theta_2} = \dfrac{n_2}{n_1} = \dfrac{v_1}{v_2} = \dfrac{\lambda_1}{\lambda_2}$
$\vec{p} = m\vec{v}$	$E_k = \dfrac{1}{2}mv^2$	$v = f\lambda$	$\lambda = \dfrac{d\sin\theta}{n}$
$\vec{F}\Delta t = m\Delta\vec{v}$	$E_p = mgh$	$f = \left(\dfrac{v}{v \pm v_s}\right)f_s$	$\lambda = \dfrac{xd}{nl}$
$W = |\vec{F}||\vec{d}|\cos\theta$	$E_p = \dfrac{1}{2}kx^2$		
$W = \Delta E$			
$P = \dfrac{W}{t}$			

$$P = \frac{W}{t} \text{ or } P = \frac{\Delta E}{\Delta t}$$

$$0.4\times10^{-3} = \frac{\Delta E}{1s}$$

$$E_{TOT} = 0.4\times10^{-3}\ J$$

$$E_{TOT} = n(E_{photon})$$

$$0.4\times10^{-3} = n\left(\frac{(6.63\times10^{-34})(3.0\times10^8)}{600\times10^{-9}}\right)$$

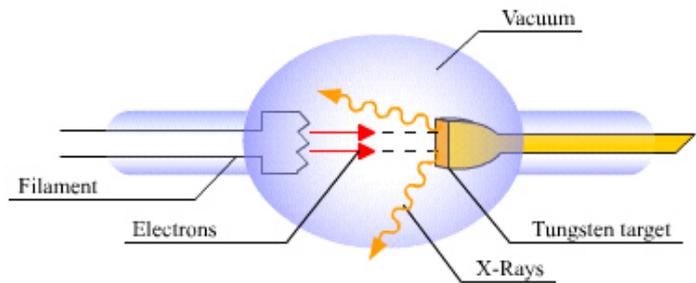$$0.4\times10^{-3} = n(3.315\times10^{-19})$$

$$n = 1.206636...\times10^{15}$$

$$\boxed{n \approx 1.2\times10^{15}\ photons}$$

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X-Ray Production

Sound is produced when a fast moving hand is quickly decelerated.	X-rays are produced when fast moving electrons are quickly decelerated.

Physics Principal #5: Conservation of Energy

Q4: Calculate the maximum frequency of x-rays that are produced in an x-ray tube in which the potential difference across the tube is 3.25×10^4 V.

Electricity and Magnetism

$$\left|\vec{F}_e\right| = \frac{kq_1q_2}{r^2} \qquad \Delta V = \frac{\Delta E}{q} \quad E_p = q\Delta V$$

$$\left|\vec{E}\right| = \frac{kq}{r^2} \qquad I = \frac{q}{t}$$

$$\vec{E} = \frac{\vec{F}_e}{q} \qquad \left|\vec{F}_m\right| = Il_\perp\left|\vec{B}\right|$$

$$\left|\vec{E}\right| = \frac{\Delta V}{\Delta d} \qquad \left|\vec{F}_m\right| = qv_\perp\left|\vec{B}\right|$$
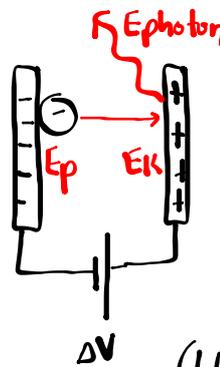
E_{photon}

$E_p \rightarrow E_K \rightarrow E_{photon}$

$q\Delta V \rightarrow \frac{1}{2}mv^2 \rightarrow hf$
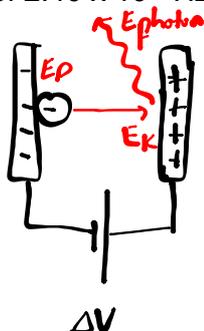
$q\Delta V \rightarrow hf$

$(1.60 \times 10^{-19})(3.25 \times 10^4) = (6.63 \times 10^{-34})f$

$f = 7.84 \times 10^{18}$ Hz

Why did this question specify "the maximum frequency"?

Q5: Calculate the operating potential of an x-ray tube which produces x-rays with a maximum frequency of 2.40×10^{18} Hz.

$E_p \rightarrow E_k \rightarrow E_{photon}$

$q\Delta V \longrightarrow hf$

$(1.60 \times 10^{-19})(\Delta V) = (6.63 \times 10^{-34})(2.40 \times 10^{18})$

$\Delta V = 9945V \quad = 9.945 \times 10^{3}$

$\approx 9.95 \times 10^{3}$

$9.6 \times 10^{2} V$

9	9	5	3