6.1 Quantum Physics. Particle Nature of Light

- Particle nature of Light
  - Blackbody Radiation
  - Photoelectric Effect
- Properties of photons
  - Ionizing radiation
  - Radiation damage
- x-rays
  - Compton effect
  - X-ray diffraction

Photons

When light exchanges energy with atoms it behaves as a particle - called the photon

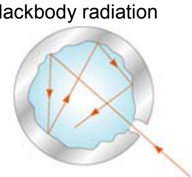
The energy of a photon is proportional to the frequency f of light

$$E_{photon} = hf$$

Planck's Constant $h=6.626\times10^{-34}$ J• s

Thermal Radiation

Blackbody radiation



A container at temperature T in equilibrium with electromagnetic radiation.
Light is absorbed and emitted by the walls.
At equilibrium the spectrum of the light only depends on the temperature.

Spectrum of Blackbody radiation

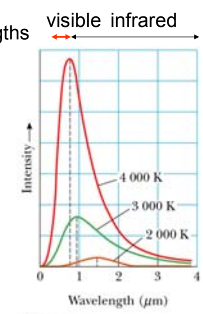
A wide spectrum of wavelengths is produced.

The total intensity increases with temperature

The peak wavelength decreases with temperature
Wien's displacement law

$\lambda_{max}T= 0.2898\times10^{-2}$mK

The intensity goes down at low wavelengths (I->0, as λ-> 0)



Demonstration of blackbody radiation

A tungsten filament light bulb is approximately a black body radiator.

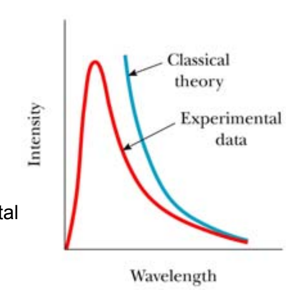
http://www.physics.ucla.edu/demoweb/demomanual/astronomy/quantum_mechanics/blackbody_radiation.html

Disagreement with classical theory of light

The classical theory predicts that intensity continues to increase with decreasing wavelength.

"Ultraviolet Catastrophe"

To explain the experimental data Planck proposed the quantum hypothesis.



Planck's constant

Max Planck

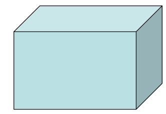
Planck proposed that light could only have certain energies

E=hf

Then the energy of oscillators in the black body could only have certain fixed values

Classical and Planck picture

Suppose we have a box that contains light waves with different wavelengths. The energy is contained in energy states containing particles with different energies



Classical theory predicts that the number of energy states (like standing waves) increased with decreasing wavelength.

Planck proposed that in addition the short wavelength particles are more "energetically expensive"

So at short wavelength, they would be hard to produce. This explains the peak in the black body spectrum

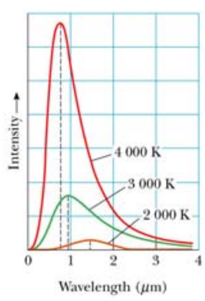
Quantum explanation for the Wein Effect.

- The blackbody spectrum reflects the distribution of photon energies.
- The peak wavelength reflects the average energy.
- The average photon energy increases linearly with temperature

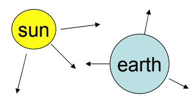
from $\lambda_{max}T = \text{constant}$

since $\lambda = \frac{c}{f}$

then $T \propto \frac{1}{\lambda_{max}} \propto \frac{hf_{max}}{c} \propto$ Average photon energy



Question



The sun has a surface temperature of 5,800 K. The solar radiation has a peak wavelength of 500 nm. The earth has temperature of about 300 K. What is the maximum wavelength of the blackbody spectrum of the earth?

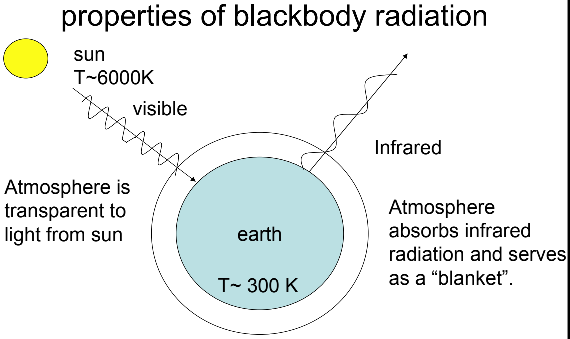
Wein Law $\lambda_{max}T = \text{constant}$

$$\lambda_{max}^{earth}T^{earth} = \lambda_{max}^{sun}T^{sun}$$

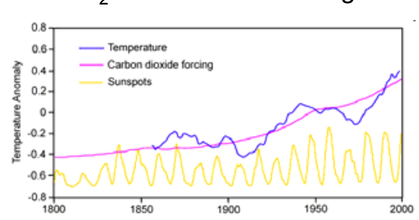
$$\lambda_{max}^{earth} = \frac{\lambda_{max}^{sun}T^{sun}}{T^{earth}} = \frac{500x10^{-9}m(5800K)}{300K} = 9.7x10^{-6}m$$

10micrometers infrared region

The "Greenhouse Effect" is based on properties of blackbody radiation



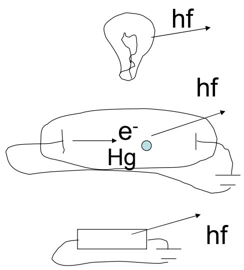
CO_2 and Global Warming



Graph showing that the observed temperature rise can easily result from the observed rise of CO_2 , based on simple numerical experiment. (Smoothed temperature data in Jones et al., 1998; CO_2 forcing data from CO_2 history, and calculated expected rise in temperature assuming 2 degree Celsius rise for CO_2 doubling; sunspot abundance from J.Lean, NASA)

http://earthguide.ucsd.edu/globalchange/global_warming/03.html

Sources of visible light



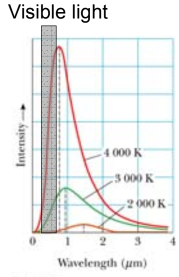
incandescent lamp
black body radiation of a heated metal filament

fluorescent bulb
emission of excited atoms

light emitting diode
emission by electron across an energy gap in a semiconductor

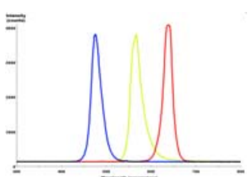
Fluorescent bulbs and LEDs are more efficient sources of light than incandescent lamps.

Tungsten Lamp light source



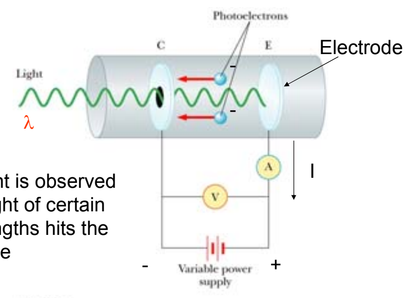
A tungsten lamp is inefficient as a light source because the spectrum at temperatures lower than the melting point includes a large amount of useless infrared radiation.

Light emitting diode LED



Light emitting diodes are more efficient as an illumination source because the spectrum is not based on blackbody radiation.
The light can be produced at specific wavelengths in the visible region

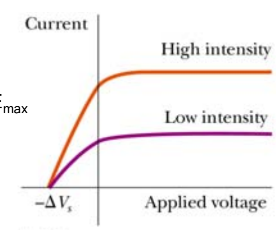
Photoelectric effect.



A current is observed when light of certain wavelengths hits the electrode

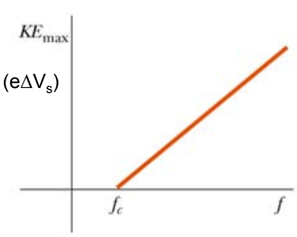
Photoelectric effect

$e\Delta V_s = KE_{max}$



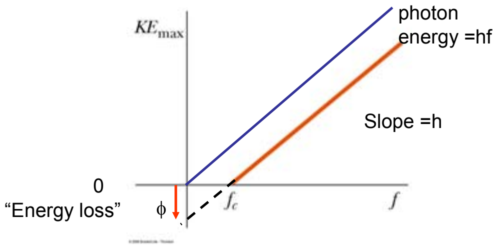
The stopping voltage ΔV_s is a measure of the kinetic energy of the photo electrons.
When the ΔV_s is high enough electrons don't reach the electrode C.

Photoelectric Effect



Kinetic energy rises linearly with the frequency of light.

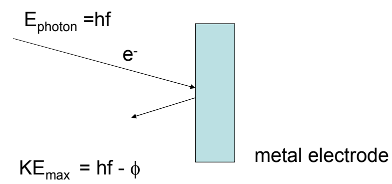
Einstein's explanation



$KE_{max} = E_{photon} - \phi = hf - \phi$

ϕ is the work function, the energy needed to remove the electron from the electrode.

Photon concept



A photon interacts with the electron
The light energy can have only specific values.
Light energy is quantized

Properties of Photons

Photon energies - Interactions of light with matter.

- Ionizing radiation
- Radiation damage

x-rays

- Compton effect
- X-ray diffraction

Photon Energy

Find the energy of a photon with a wavelength of 500 nm. Use units of electron volts (1eV= 1.60×10^{-19} J)

$$E = hf = h\frac{c}{\lambda} = 6.63 \times 10^{-34}\,\text{Js}\left(\frac{3 \times 10^{8}\,\text{m/s}}{500 \times 10^{-9}\,\text{m}}\right) = 4.0 \times 10^{-19}\,\text{J}$$

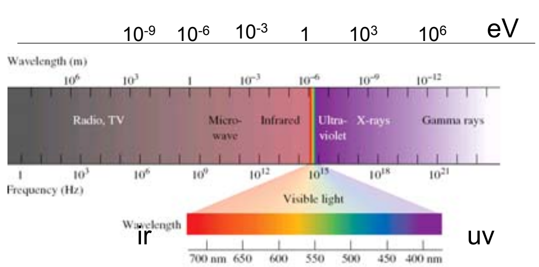
$$E = \frac{4 \times 10^{-19}\,\text{J}}{1.6 \times 10^{-19}\,\text{J/eV}} = 2.5\,\text{eV}$$

An electron volt is the energy change in moving an electron across a potential of 1 volt.

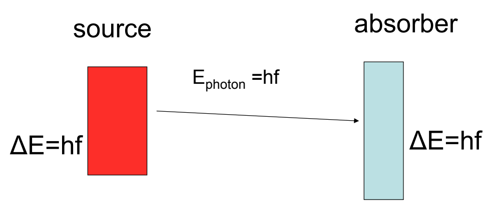
A few electron volts is the energy of electrons in molecules. This is why visible light is absorbed by molecules (pigment molecules).

Photon Energies (eV)

$E = hf = hc/\lambda$



Photon concept



Light energy is has specific energies i.e. is quantized in the interaction of light with matter.
Photons of different wavelengths, interact with different molecular properties- either in the generation of the photon or the absorption of the photon.

Photon Energies

light	Typical Wavelength (m)	Typical Photon energy (eV)	Molecular interactions	applications
radio	10	10-7 eV	nuclear magnetic	NMR imaging
microwaves	10-2	10^{-4} eV	Molecular rotations	Microwave oven cell phone
Infrared	10^{-5}	10^{-1} eV	Molecular vibrations	Heat lamp
Visible	400-700 nm	2-3 eV	Low energy electrons (pigments)	Vision Photosynthesis Photography
Ultraviolet	200-300 nm	4-5 eV	bonding electrons	Radiation damage Skin cancer
X-rays	1 nm	10^{4} eV	Electrons scattering, tightly bound electrons	X-ray imaging X-ray diffraction

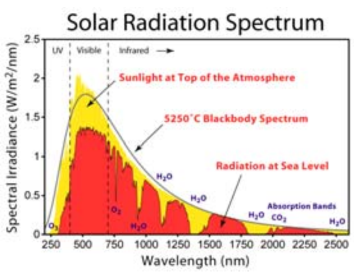
Microwave Oven

f =10GHz

hf =4x10^{-5} eV

Heats by exciting molecular rotations and vibrations.

Cell phones use the same frequency range but at much lower intensity.



- Infrared light absorbed by vibrations of gas molecules
- Visible light absorbed by electronic transitions in pigment
- UV radiation – 4-5 eV photons cause radiation damage by altering DNA (UV-B radiation at 320-290 nm)
- Ozone in the atmosphere protects by absorbing UV radiation.

UV light damage to inkjet prints

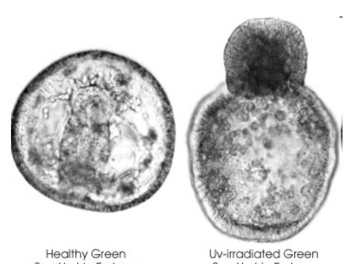
UV light treated Uv protected

Radiation damage to DNA

UV light

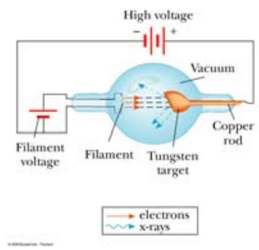
Altered DNA

Biological effects of uv radiation



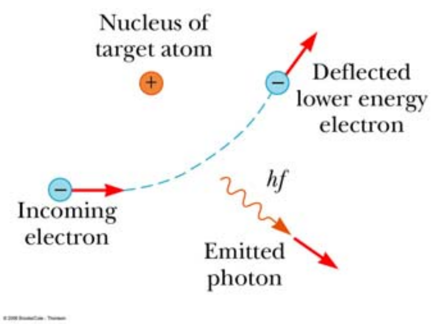
Organisms living in shallow sea water are susceptible to increased uv radiation.

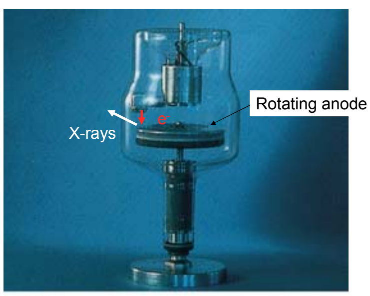
X-rays



X-rays are produced by electrons accelerated through high voltages $V \sim 10^{4}$ V
Photon energies ~ 10^{4} eV

Generation of x-rays by electrons



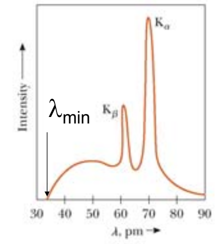


X-ray source

X-rays

A Quantum Effect.
The maximum photon energy is ~ equal to the kinetic energy of the electron.

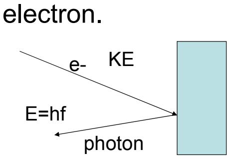
$$e\Delta V = hf_{max} = \frac{hc}{\lambda_{min}}$$



X-ray spectrum produced by 35 keV electrons hitting a molybdenum target.

Question

Find the minimum x-ray wavelength for a 35 kev electron.



hf=KE
(neglect work function- it is small compared to x-ray energies)

KE= 35×10^{3} eV x (1.6×10^{-19} J/eV) = 5.6×10^{-15}J

$$E_{max} = hf_{max} = \frac{hc}{\lambda_{min}} = KE$$

$$\lambda_{min} = \frac{hc}{KE} = \frac{6.63\times10^{-34}\,Js(3.0\times10^{8}\,m/s)}{5.6\times10^{-15}\,J} = 3.6\times10^{-11}m$$

0.036 nm

x-ray imaging

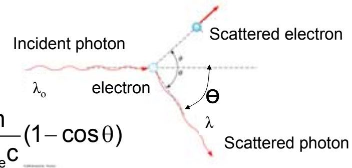
x-ray photograph of Wolfgang Roentgen's wife's hand.

x-rays penetrate soft tissue (light atoms) but are absorbed by heavy metal atoms. eg.Calcium, Gold

Compton scattering of x-rays.

High energy photons knock electrons out of atoms

The wavelength of a photon scattered from an electron is increased due to loss of photon energy.



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

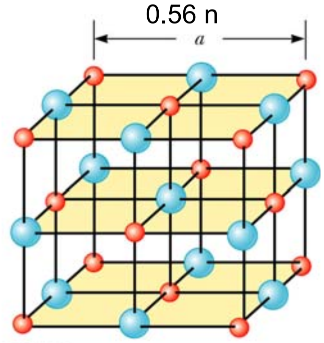
Lower energy –> Longer wavelength

X-ray diffraction

- X-rays have wavelengths close to atomic dimensions
- Crystalline solids have an ordered array of atoms that scatter x-rays much like a three-dimensional diffraction grating
- The x-ray diffraction pattern from crystals of molecules can be used to determine the density of scattering electrons (i.e. the electron density) and thus the molecular structure.

NaCl Crystal – an ordered array of atoms

0.56 n



Diffraction of x-rays from a crystal.

Each atom acts as a wave source.

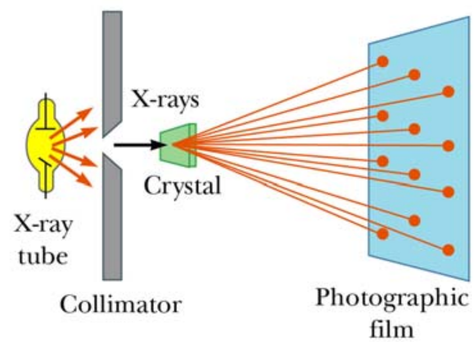
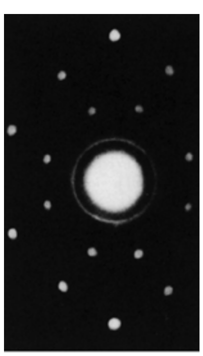
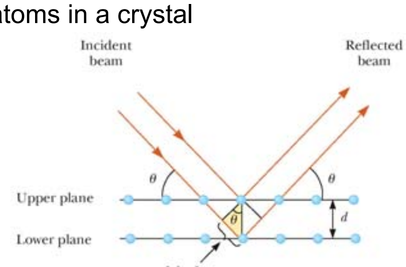


Fig. 27-11, p.883

X-ray diffraction pattern of NaCl

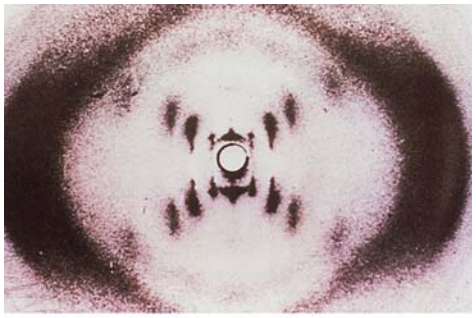


Condition for diffraction of x-rays from planes of atoms in a crystal



Bragg's Law

$2d\sin\theta = m\lambda$ m=1, 2, 3 ....



X-ray diffraction pattern from a crystalline fiber of DNA. Watson
And Crick used this data to deduce the structure of the DNA molecule

DNA structure
determined by
x-ray diffraction