Blackbody radiation

All bodies emit and absorb radiation. When a body`s temperature is constant, the body is in thermal equilibrium. To make the temperature is constant, the body must absorb thermal energy at the same rate as it emits it, and the blackbody is the example about these bodies, which can be preparing by drill a small hole in the wall of the container. The radiation entering the hole will be reflected around inside the container and then absorbed. Only a small fraction of the entering rays will be reemitted through the hole.

Black body: is an ideal body which allows the whole of the incident radiation to pass into itself, without reflecting the energy.

Thermal radiation: is the electromagnetic radiation emitted by a body as a result of its temperature.

Examples of blackbodies

Body painted in black (reflecting very little light).

Cavity connected by a small hole to the outside.

Total radiancy: The total energy emitted per unit time per unit area.

Physicists can study the properties of intensity versus wavelength (called spectral distribution) at fixed temperatures. The measurements of the variation of the blackbody can be explained according to the spectral distribution which is shown in figure (1). The important observations from this figure is:

1. According to Wien`s displacement Law, the maximum of the spectrum shifts to small wavelengths (large frequencies) at the temperature is increased, and not only the amount of thermal radiation will increase with temperature but also the color of glowing hot body will change from red to blue-white.
   $\lambda_{max} \times T = 2.898 \times 10^{-3}\ m.K$ (Wien`s displacement Law)

2. According to Stefan-Boltzmann law, the total power radiated (radiancy) increases with the temperature.
   $R(T) = \in \sigma T^4$ Stefan-Boltzmann law

   σ: The constant and it is equal to 5.67×10^{-8} W/(m^2.K^4).

ϵ: The emissivity and it is equal to 1 for the idealized blackbody.

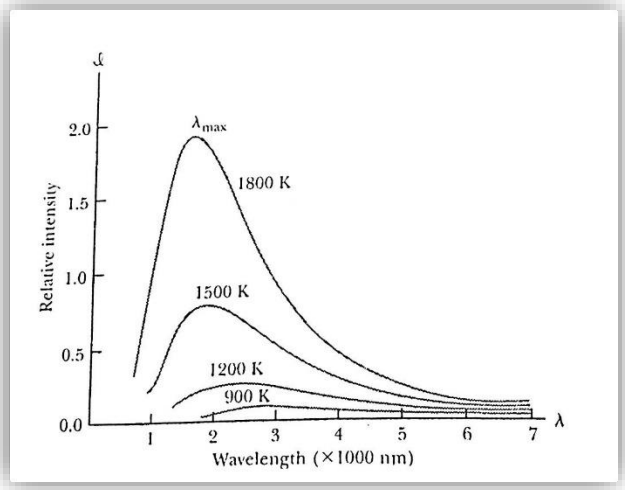


Figure (1) : The spectral radiance of blackbody

The classical theory explained the blackbody radiation as in the part (a) in figure (2), and this results known as Rayleigh-Jeans formula, but this formula can not explain the radiation in the short wavelengths region (high frequencies). The relativity theory succeed to explain this problem by depending on Planck`s radiation law.

$$I = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Also, Planck stated that the electromagnetic origin can only have discrete energies

$$E = h\upsilon$$

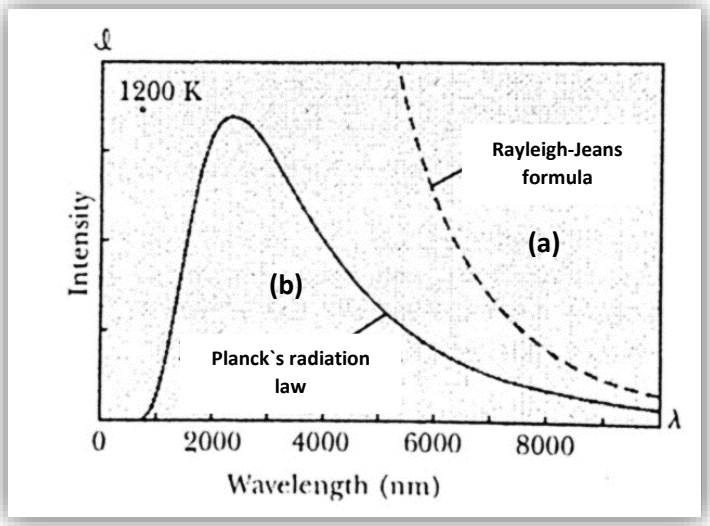


Figure (2): The explanation of the classical and relativity theories

Photoelectric effect

The simplest evidence for the quantization of radiation energy comes from the explanation of the photoelectric effect. Hertz in 1887 noticed that (when the electromagnetic radiation interacts with electrons within metals, it increases the kinetic energy of the electron, because electrons in metals are weakly bound, so, the light can give the electrons enough extra kinetic energy to allow them to escape the metal. The ejected electrons is called photoelectron.

Work function: The minimum kinetic energy that allows electrons to leave the metal.

Stopping potential: It is the voltage which is sufficient to stop all the photoelectrons.

In the photoelectric effect experiment, the incident light falling on the emitter (cathode) ejects electrons. Some of the electrons travel toward the collector (anode) where the voltage is imposed by the power supply. The photocurrent (I) measured in the ammeter arises from the flow of photoelectrons from emitter to collector and it depends on the intensity (brightness) and frequency (color) of the shine on the metal surface.

Experimental fact of the photoelectric effect

1. The kinetic energies of the photoelectrons are independent of the light intensity.
2. The maximum kinetic energy of the photoelectrons, for a given emitting metal, depend only on the frequency of the light.
3. No photoelectron are produced for frequencies below the threshold frequency.

The classical theory notes about the photoelectric effect

1. It predicts that the total energy in a light wave increases as the light intensity increases, so, the electrons should have more kinetic energy if the light intensity is increased.
2. It is unable to explain the stopping potential.

3. It can not explain the relation between the maximum kinetic energy with the frequencies, because the maximum kinetic energy depend on the value of the light frequency and not on the intensity.
4. The existence of a threshold frequency is inexplicable in classical theory.
5. It does predict that the number of photoelectrons ejected will increase within intensity in agreement with the experiment.

The relativity theory notes about the photoelectric effect

1. It predicts that for extremely low light intensities, a long time would elapse before any electron could obtain sufficient energy to escape.
2. The kinetic energies of the photoelectron depend on the light frequency, but not the light intensity.
3. It predicts that the stopping potential will be linearly proportional to the light frequency, with a slope h/e

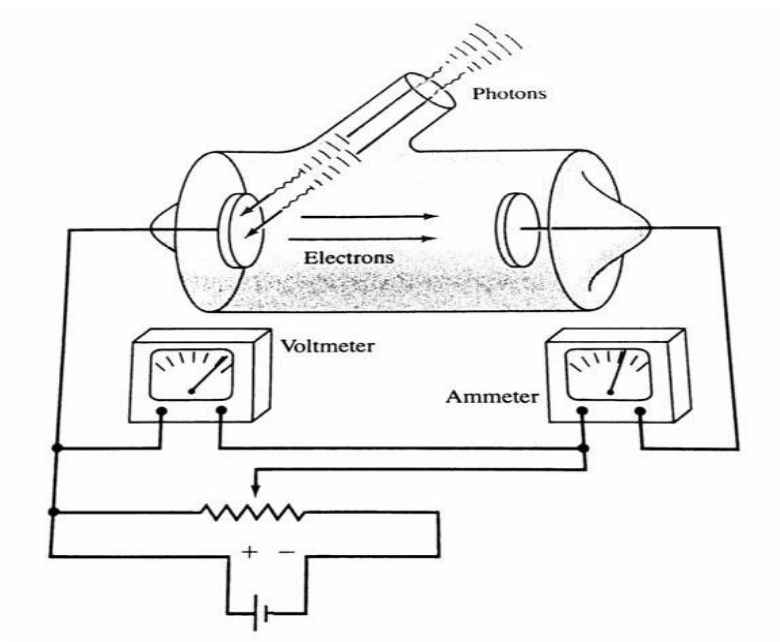
$$eV_o = \frac{1}{2}mv^2 = hf - hf_o = h(f - f_o)$$

$\emptyset = hf_o$ stopping potential

f_o: the threshold frequency

$h\upsilon = W + K.E$

$h\upsilon = h\upsilon_c + K.E$



The photoelectric effect experiment

Example :

The energy required to remove an electron from sodium is 2.3 eV. Does sodium show a photoelectric effect for orange light with λ = 6800 Å ?

Sol^n.

Given W = 2.3 eV = $2.3 \times 1.6 \times 10^{-19}$ joules.

If λ_0 is threshold wavelength for sodium, then

$$W = \frac{hc}{\lambda_0}$$

Or

$$\lambda_0 = \frac{hc}{W} = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{2.3 \times 1.6 \times 10^{-19}} m = 5380 \times 10^{-10} m = 5380 Å$$

From definition threshold wavelength is the longest wavelength that is capable of showing photoelectric effect. Hence, orange light with λ = 6800Å can not show photoelectric effect when incident on the surface of sodium with work function 2.3 eV.

Example :

The work function of potassium is 2.0 eV, when ultraviolet light of wavelength 3500Å falls on potassium surface. Calculate the maxiumum kinetic energy of emitted photoelectrons in eV. Given Planck's constant $\lambda = 6.62 \times 10^{-34}$ Js.

Sol^n :

Given W = 2.0 eV, $\lambda = 3500 \times 10^{-10}$ m

Energy of a photon of incident ultraviolet light

$$E = \frac{hc}{\lambda} = \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{3500 \times 10^{-10}} joule$$

$$= \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{3500 \times 10^{-10} \times 1.6 \times 10^{-19}} eV = 3.546\ eV.$$

Einsteins photoelectric equation is

$$\frac{hc}{\lambda} = KE_{max} + W$$

∴ Maximum kinetic energy

$$KE_{max} = \frac{hc}{\lambda} - W$$

$$KE = 3.456\ eV - 2.0\ eV = \mathbf{1.456\ V}$$

Example :

Calculate the value of the retarding potential needed to stop the photoelectrons ejected from a metal surface of work function 1.2 eV with light of frequency 5.5×10^{14} sec^{-1}.

Sol^{n} :

According to Einstein's photoelectric equation if V_0 is the retarding potential, we have

$$eV_0 = h\nu - W$$

Here $e = 1.6 \times 10^{-19}$ *joule*, $\nu = 5.5 \times 10^{14}$ sec^{-1}

And $W = 1.2\ eV = 1.2 \times 1.6 \times 10^{-19}$ *joule*

$\therefore$ $1.6 \times 10^{-19}\ V_0 = 6.6 \times 10^{-34} \times 5.5 \times 10^{14} - 1.2 \times 1.6 \times 10^{-19}$

Or $1.6 \times 10^{-19}\ V_0 = 1.71 \times 10^{-19}$

$\therefore$ *retarding potential,* $V_0 = \frac{1.71 \times 10^{-19}}{1.6 \times 10^{-19}} = \mathbf{1.06\ volt.}$

= 5.67 x10^{-8} x 5800

= 6.42 x10^{7} W/m2

Example :

A Green light has a wavelength of 525 nm. Determine the energy for the green light in joules.

Sol.:

$c=\lambda\times\upsilon$

$\upsilon=3\times10^{8}/525$

$\upsilon=5.71\times10^{14}$ s

$E=h\times\upsilon$

$= (6.626\times10^{-34})\times(5.71\times10^{14})$

$= 3.78\times10^{-19}$ J/photon

Example (4):

A furnace emits radiation at 2000 K. Treating it as a black body radiation, calculate the monochromatic radiant intensity at 1 micron m wavelength

Sol.:

$$I = \frac{2\pi c^2 h}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$$

$$I= 2.81 * 10^{7}\ W/m2$$

Homework: find how can we get the above answer in example (4)?

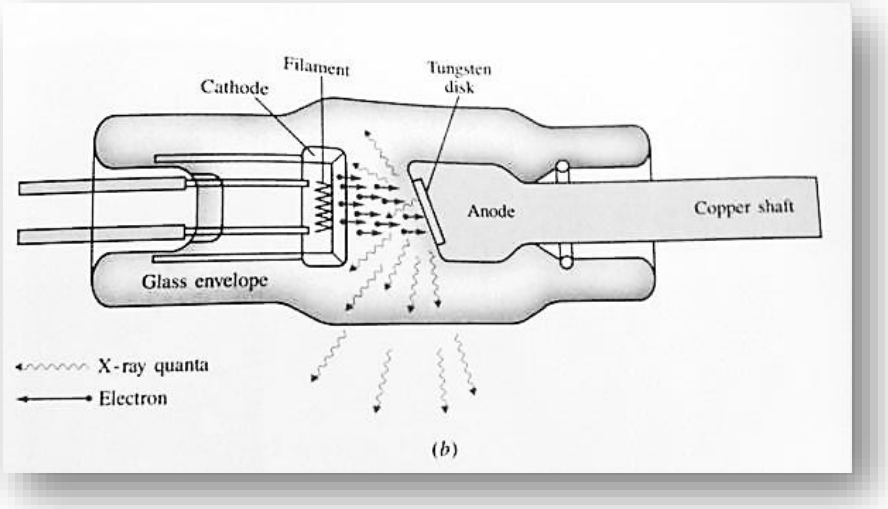
X-ray production

The x-ray production is inverse process to the photoelectric effect that means the electron gives its energy and create a photon and lose kinetic energy.

The x-rays are produced by the Bremsstrahlung effect. This process deals with which photons are emitted by an electron slowly down. Electron of energy E_i passing through the electric field at a nucleus is accelerated and product a photon of energy ($E=h\upsilon$). The final energy of the electron is determined from the conservation of energy to be:

$E_f=E_i-h\upsilon$

The current passes through a filament and it produced numbers of electrons by thermionic emission. These electrons are focused by the cathode structure into a beam and are accelerated by potential (~40 volts) until they impinge on a metal anode surface, producing-rays by Bremsstrahlung as it stop in the anode material. Much of the electron`s kinetic energy is lost by heating the anode material and not by Bremsstrahlung.



Schematic of x-ray tube where x-rays are produced by the Bremsstrahlung effect

The tube has targets of tungsten, molybdenum and chromium. It is evacuated so that the air between the filament and anode will not scatter the electrons. The x-rays produced pass through the sides of the tube and can be used for a larger number of applications, including medical diagnosis and therapy, fundamental research in crystal and liquid structure, and industrial purposes.

The x-ray wavelength range from 10^{-8} – 10^{-15} m.

The conservation of energy requires that the electron kinetic energy equal to maximum photon energy.

$$eV_o = h\upsilon_{max}$$

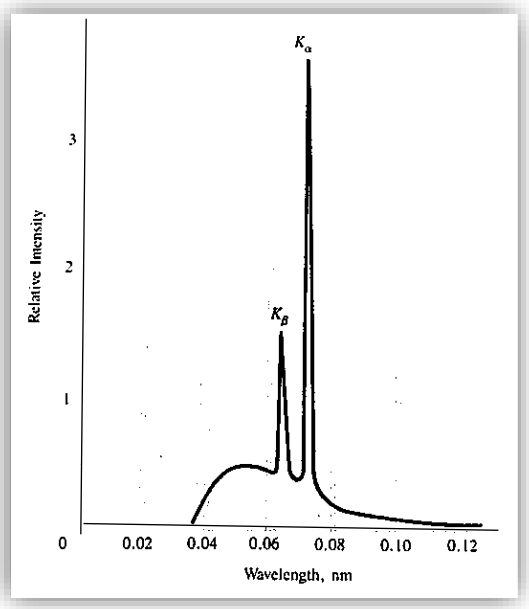
$$eV_o = \frac{hc}{\lambda_{max}}$$

$$\lambda_{min} = \frac{hc}{eV_o}$$

This equation is called (Duane-Hunt rule)

The intensity of the x-ray increases with the square of the atomic number of the target. The intensity proportional to the square of the voltage used to accelerate the electrons.

The characteristic X-ray emission which is shown as two sharp peaks in the illustration below occur when vacancies are produced in the n=1 or K-shell of the atom and electrons drop down from above to fill the gap .The X-ray produced by transitions from when n=2 to n=1 level are called K-alpha X-ray , and those for n=3 to n=1 transitions are called K-beta X-ray.



The typical x-ray spectrum

The continuous distribution of X-rays which forms the base for two sharp peaks above is called "bremsstrahlung" radiation.

"Bremsstrahlung" means "braking radiation" and it describes the radiation which is emitted when electrons are braked, when they are fired at a metal target. The continuous distribution of radiation of radiation which becomes more intense and shifts toward higher frequencies when the energy of the bombarding electrons is increased .

X-ray production typically involves bombarding a metal target in an X-ray tube with high speed electrons which have been accelerated by tens to hundreds of Kilovolts of potential . The bombarding electrons can eject electrons from the inner shells of the atoms of the metal target . Those vacancies will be quickly filled by electrons dropping down from higher levels, emitting X-rays with sharply defined frequencies associated with the difference between the atomic energy levels of the target atoms.

Characteristic X-rays are used for the investigation of crystal structure by X-ray diffraction. Crystal lattice dimension may be determined with use of Bragg ,s law in a Bragg spectrometer.

X-Ray diffraction and Bragg`s law

An X-ray incident on a sample will be transmitted or it will be scattered by the electrons of the atoms in the material. All the atoms in the path of the X-ray beam scatter X-rays. So, the peaks formed when two scattered X-rays waves with phases separated by an integer number of wavelength constructively interfere to make a new wave with a larger amplitude.

Bragg's law can easily be derived by considering the conditions necessary to make the phases of the beams coincide when the incident angle = reflecting angle. The second incident beam b continues to the next layer where it is scattered by atom c. The second beam must travel the extra distance BC + CD if the two beams a and b are to continue travelling adjacent and parallel. This extra distance must be an integral (n) multiple of the wavelength for the phases of the two beams to be the same.

$n\lambda=BC+CD$

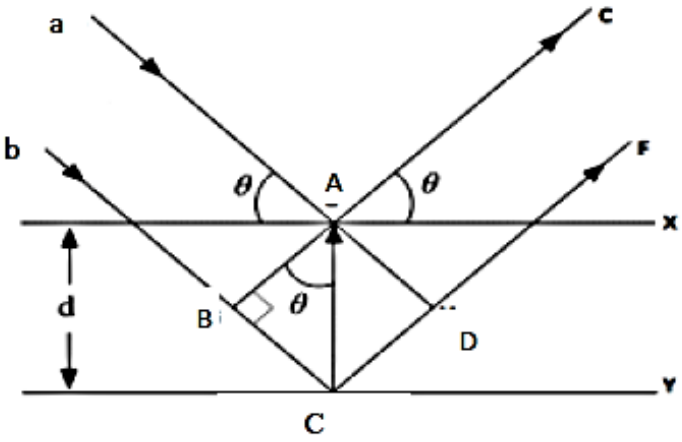
$BC=d\sin\theta$

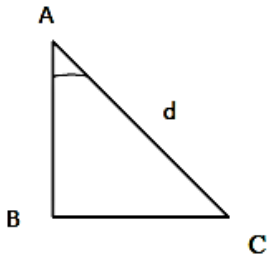
Since $BC=$ we have :

$n\lambda=2BC$

Then after substitution gives : Bragg's law

$n\lambda=2$ d sinθ





Example 1. (About x-ray production)

What is the short wavelength cutoff of x-rays produced by 10.000eV electrons striking the target of an x-ray tube?

$$\lambda_{min} = \frac{hc}{eV_o}$$

$$= \frac{1240eV.nm}{10^4\ eV} = 0.124nm$$