Chapter 2

The failure of the classical theory

According to classical electromagnetic theory, electromagnetic energy is carried by waves. This leads us to conclusion that energy flows continuously. We know that the flow of electromagnetic energy is not continuous, but is in the form of discrete bundles of energy that is, we say that electromagnetic energy is quantized, and also that electromagnetic system can exist only in certain discrete energy states.

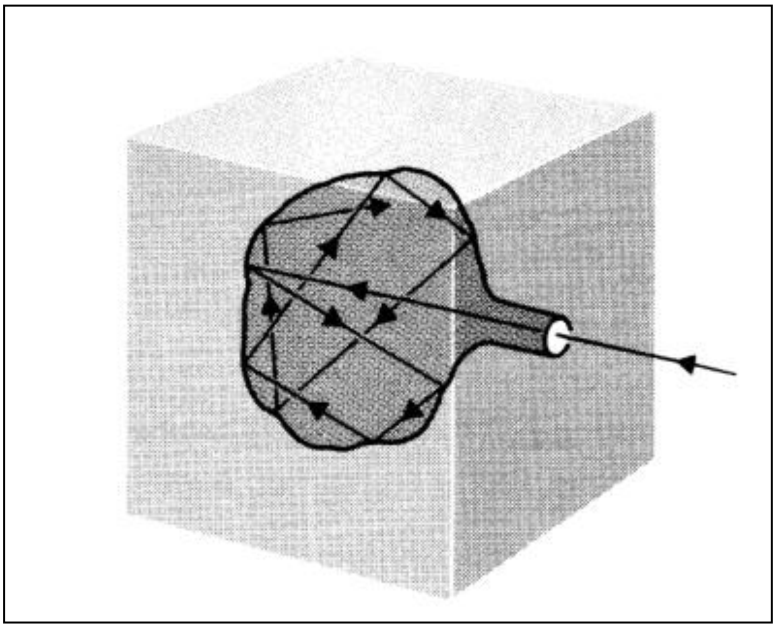
The wave theory of light could explain, interference, diffraction, and polarization, but in the beginning of the twentieth century many scientists made experimental observation connected with electromagnetic radiation. These experiments concerned the following phenomena:

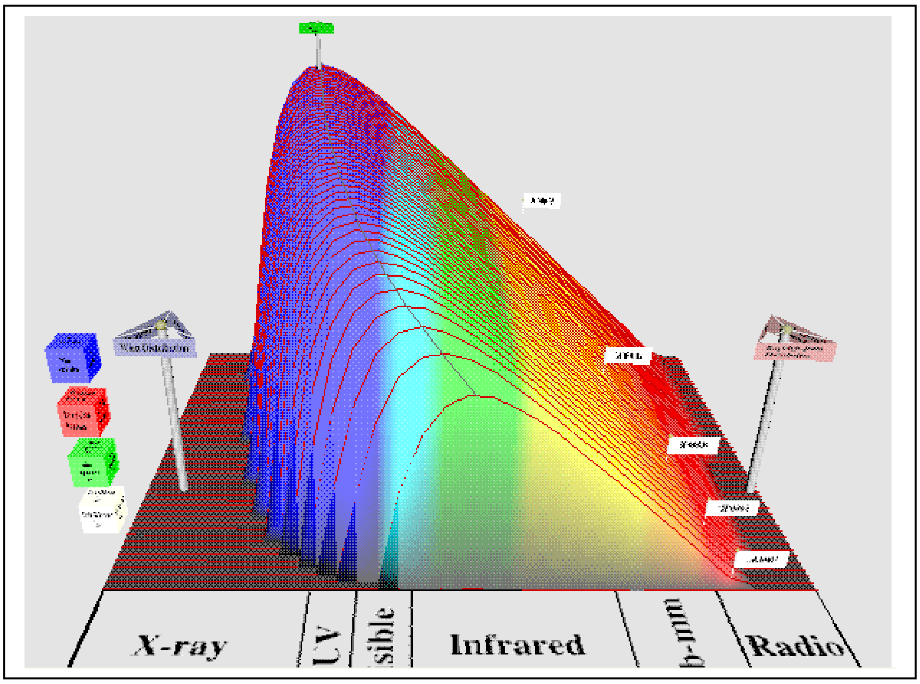
a) Blackbody radiation
b) Photoelectric effect
c) X-rays spectra
d) Compton scattering
e) Optical line spectra

Blackbody radiation

Any object in thermal equilibrium at any temperature is continuously emitting or absorbing radiation. However not all materials are equally capable of absorbing and emitting radiation in different parts of the spectrum (i.e. in the frequency range from 0)

According to Kirchoffs law any object which is a good absorber of radiation of particular wavelength is also a good emitter of radiation of the same wavelength. A body which absorbs radiation of all wavelengths is called a blackbody. A close approximation to a perfect blackbody is a cavity made out of a hollow container of any material with a narrow opening and with its inside painted with lampblack, any radiation incident on this hole will enter the cavity, be reflected from the walls of the cavity as shown in fig (1) and eventually be absorbed, and if this container is heated to any temperature T, and we analyze the radiation coming out of the hole it will contain radiation of all frequencies. So the radiation emitted from a blackbody has a continuous spectrum.





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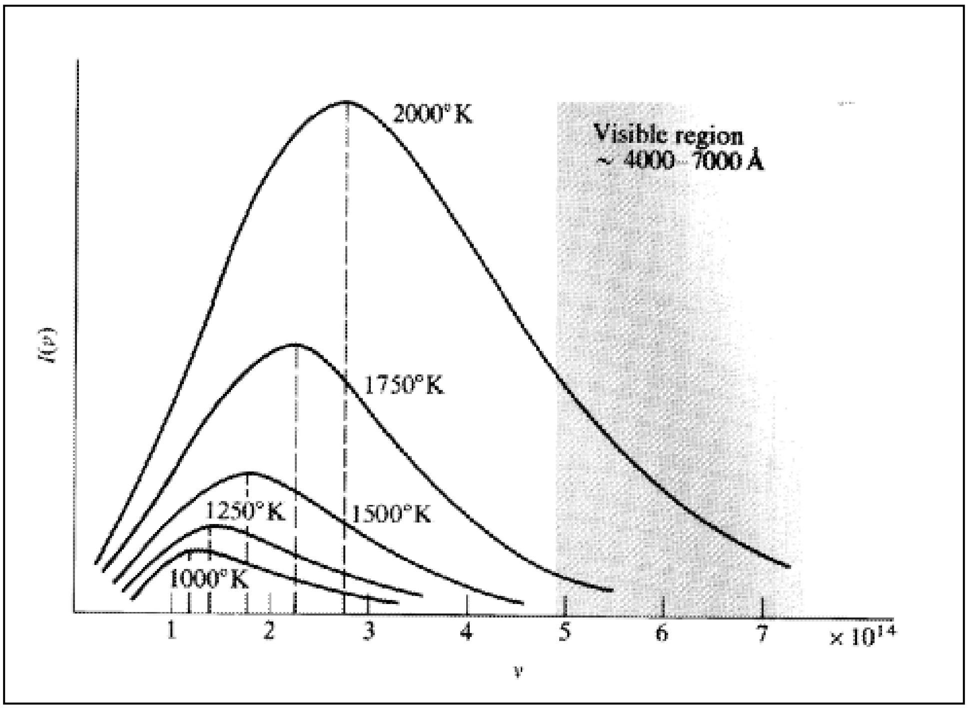
Let $I(\nu)d\nu$ be the intensity of radiation emitted between the frequency ν and $\nu d\nu$ .experimental measurements result in a plot of $I(\nu)$ versus ν as shown in fig(2) for different temperatures. Let us note some simple characteristics from these plots.

1) The distribution of frequencies is a function of temperature of a blackbody.
2) The total amount of radiation emitted $\int_0^\infty I(\nu)d\nu$ increase with increasing temperature.
3) The position of the peak maximum shifts toward higher frequencies with increasing equilibrium temperature.



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Plank hypothesis

Max plank in 1901 introduced the quantum hypothesis which was used in explaining all the experimental facts from (a) to (e).

If a physical system executes a simple harmonic motion in one dimension with frequency ν ,it can take only those energy values E which are given by the relation

$$E = nh\nu ....(1)$$

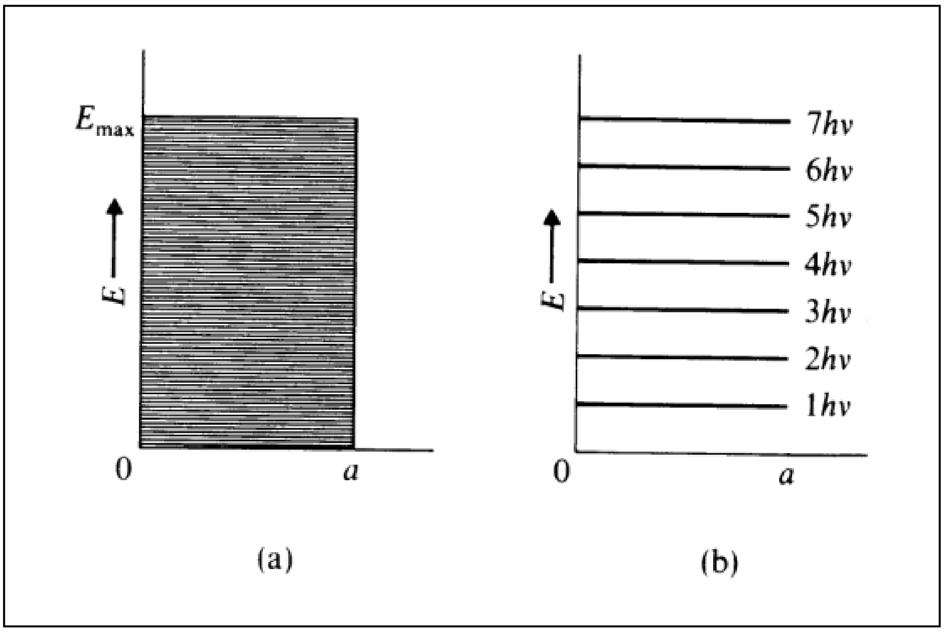
And h is constant called plank constant.

Thus plank implied that the system can exist only in certain discrete energy states given by equation. (1).

Such states are called quantum states, while n is called the quantum number.

Furthermore, the oscillations emit or absorb energy in bundles of size $h\nu$. i.e. the radiation emitted or absorbed is also quantized. The value of h is found to be 6.625×10^{-34} joule.s

Fig (3) shows the distinction between the classical theory and the plank quantization hypothesis as applied to the harmonic oscillator. as shown in fig(3-a).according to the classical theory the oscillator may take energy value (continuous range) between 0 and E_{maxi},but fig(3-b) shows that according to the quantum hypothesis only discrete energy values are allowed.



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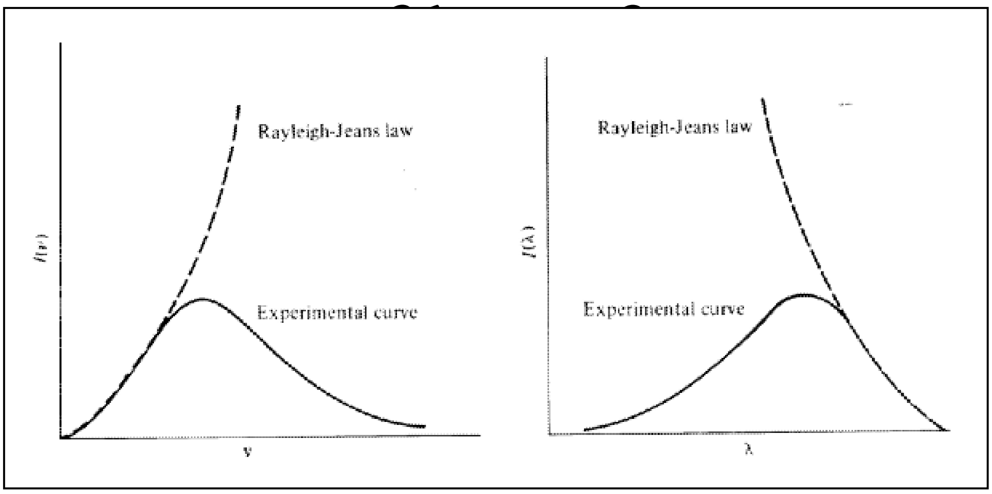
Rayleigh and Jeans law

Detailed geometrical consideration carried out by Rayleigh and Jeans, indicate that this increase in number of modes is proportional to $1/\lambda^2$ or ν^2.also when the cavity is in thermal equilibrium, each of the standing waves must be assigned on average kinetic energy KT, this leads to Rayleigh –jeans law given by

$$I(\nu)d\nu = \frac{8\pi\nu^2}{c^3}kTd\nu$$

That is $I(\nu) \propto \nu^2$, and the plot of $I(\nu)$ versus ν is shown in fig(4),where we compare this theory with the experimental data ,we see that the agreement between theory and experiment is good at low frequencies but not at high frequencies. This disagreement at high frequencies is called ultraviolet catastrophe, because according to classical theory at high frequencies $\int_0^\infty I(\nu)d\nu$ will be infinitely large, in contradiction with the experimentally measured value explanation of plank .Max plank assumed electromagnetic radiation to be emitted or absorbed in bundles of size $h\nu$, such a bundle of energy is called a quantum. For a given frequency ν ,all the quanta have the same energy, but quanta of high frequencies have high energies. Thus when a blackbody is in thermal equilibrium, the atoms and the molecules in the cavity will emit radiation only if they have energy in excess of $h\nu$. for low ν many atoms and molecules might have this excess of energy, but as ν increases the number of atoms and molecules having energy in excess of $h\nu$ decrease because the bundles become progressively bigger.



Stefan- Boltzman law

The total energy flux (or power per unit area) is the integral of the spectral emittance over all frequencies.

$$S = \int_0^\infty S_v dv$$

Graphically, this is the area under the curve in fig (5). By an elegant thermodynamic argument, which we will not attempt to reproduce here, it can be established that this total energy flux is proportional to the fourth power of the temperature.

$$S = \sigma T^4$$

This statement is called the Stefan-Boltzman law.

The constant of proportionality σ is called Stefan –Boltzman constant its value equal to

$\sigma = 5.6703x10^{-8}$ Watt/ (cm^2.k^4)

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Wiens displacement law

By a similar thermodynamic argument, it can be established that the frequency at which the spectral remittance attains its maximum is directly proportional to the temperature.

$\nu_{\max i} = const$ x T

This is called Wiens displacement law. So named it shows that as the temperature increase, the maximum in the remittance shifts to higher frequencies. The numerical value of the constant is

$cons\tan t = 5.88x10^{10}$ Hz/k

Example

At the earth surface, the energy flux is sunlight is 1.0 x10^3 watt/m^2. if a black sheet of paper faces the sun, what is the equilibrium temperature of the paper ? Assume that the bottom of the paper is insulated so that only heat loss is by blackbody radiation from the top surface.

Example a radio station operates on a frequency of 98 megacycles and radiates a power of 200 KW. How many quanta of energy are emitted per second?

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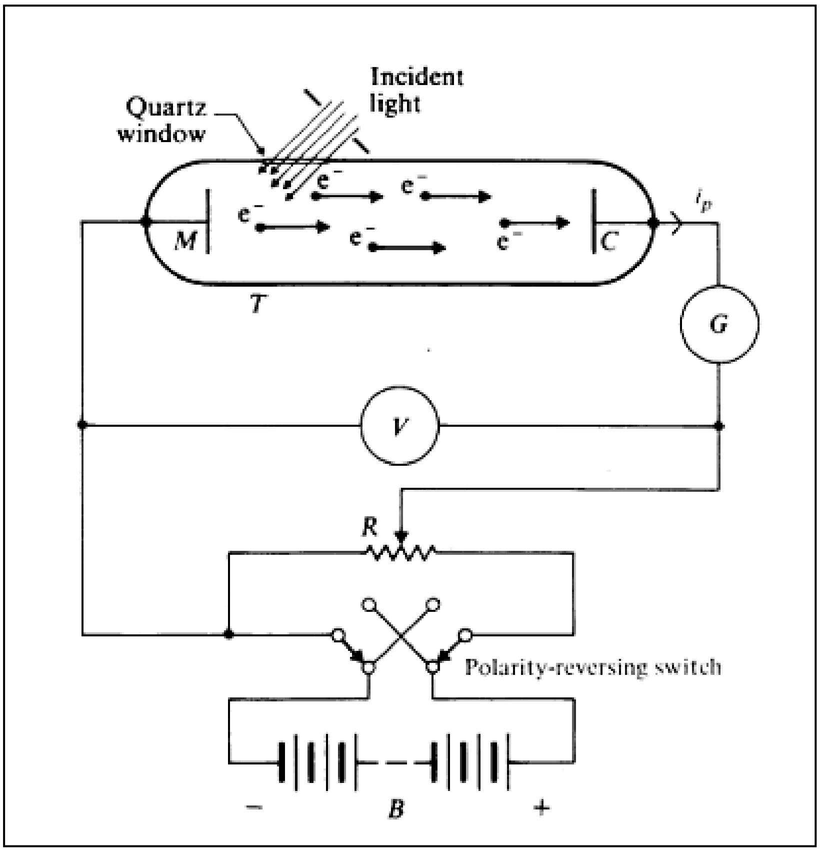
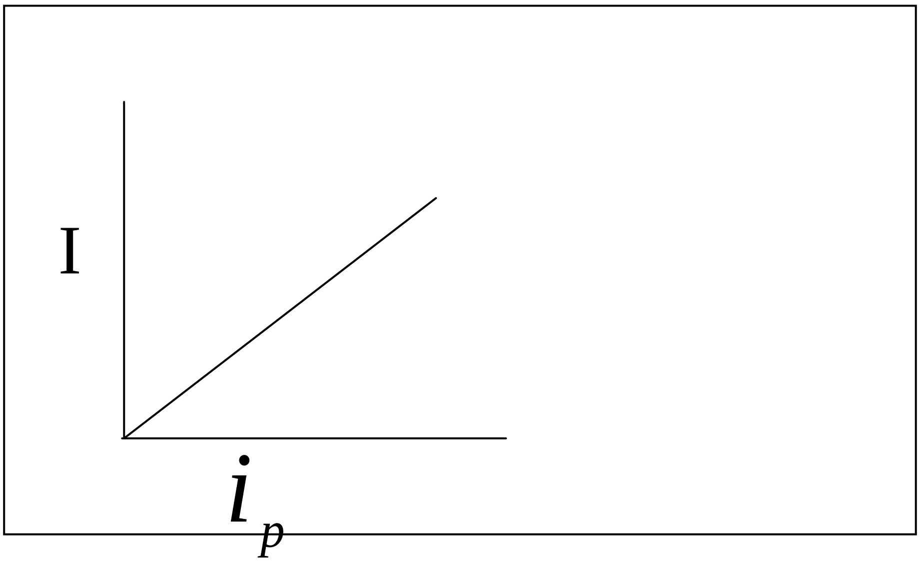
The photoelectric effect

The ejection of electron by the action of light (or electromagnetic radiation) is called photoelectric effect see fig (6)



By varying the experimental condition, one can obtain the following results.

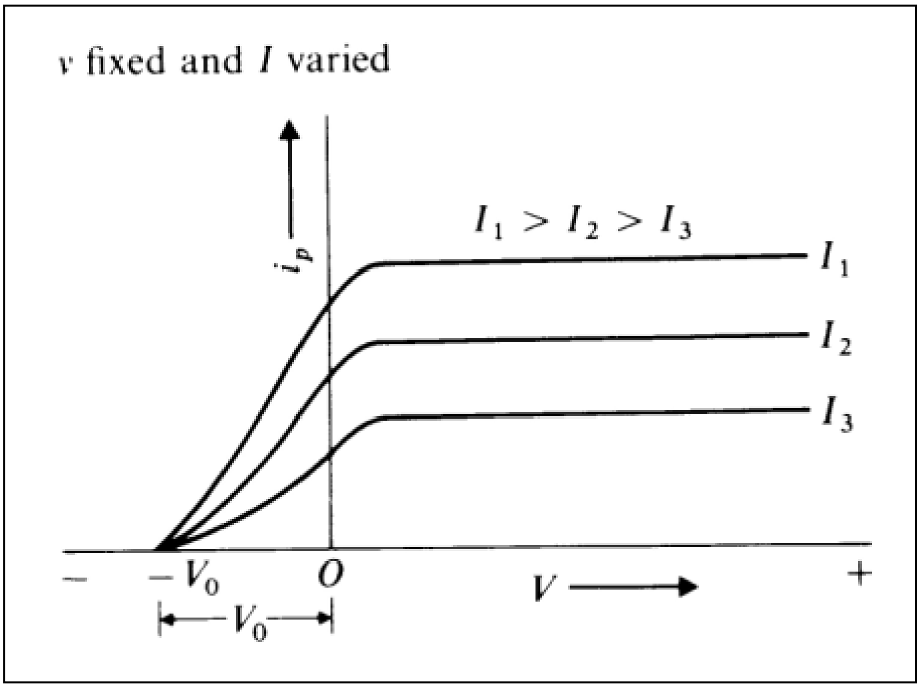
1) if ν is kept constant , the photoelectric current increases with increasing intensity I of the incident radiation. See fig(7)



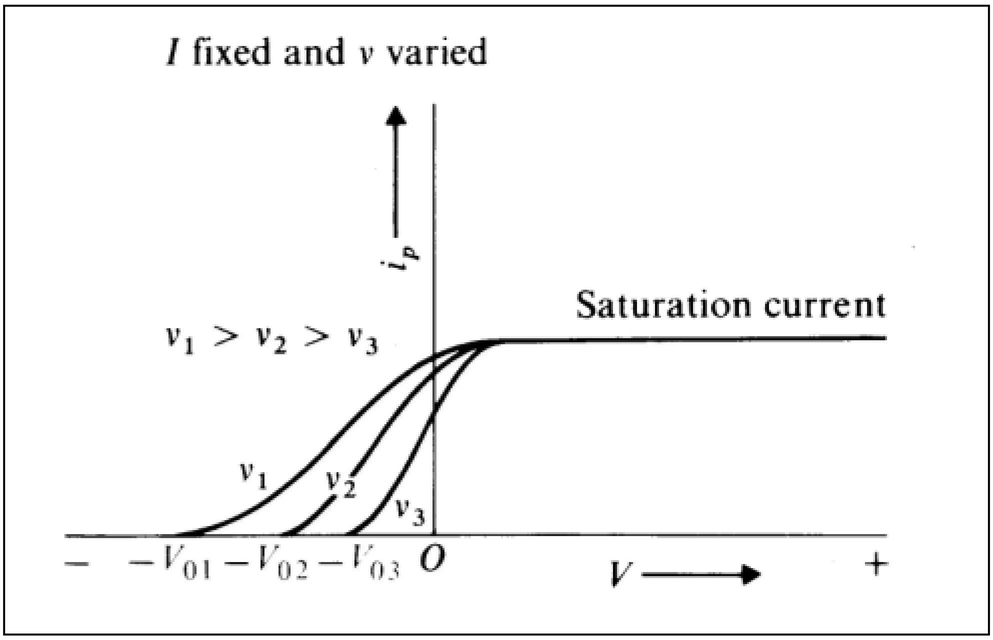
2) Photoelectrons are emitted within less than 10^{-9}s, after the surface is illuminated by light, i.e. there is no time lag between illumination and emission.

3) For a given surface, the emission of photoelectron takes place only if the frequency of the incident radiation is equal to or greater than a certain minimum frequency called the threshold frequency ν_o is different for different surfaces.

4) The maximum kinetic energy k_{maxi} of photoelectrons is independent on the intensity I of the incident light. This is obvious from fig (9), which shows that the stopping potential is the same for light of three different intensities but of the same frequency.



5) The maximum kinetic energy k_{maxi} of photoelectrons depend on the frequency of the incident radiation, this is obvious from fig (9) which shows that the stopping potential is different for different ν even though I is the same.

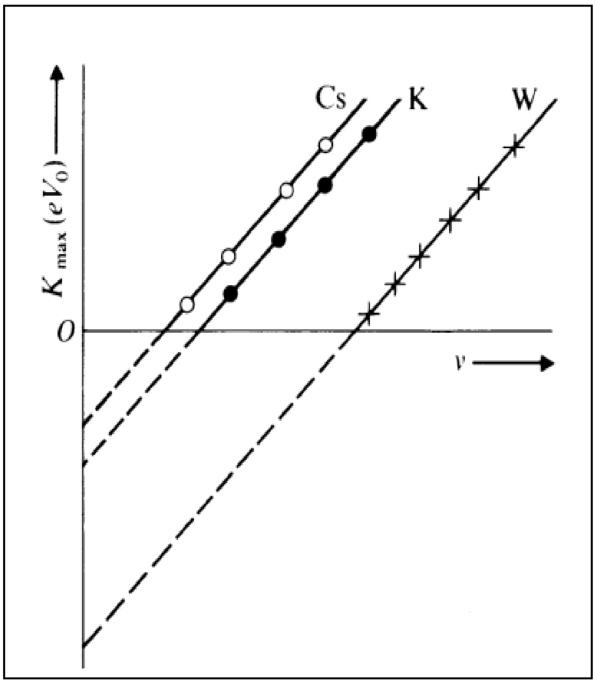


6) There is a linear relation between k_{maxi} and ν shown in fig (10), for the surfaces of three different metals cesium, potassium and tungsten

$k_{max} = a\nu + b$

Where a is the slope of the straight line and is the same for all the surfaces

, while b is the intercept and is different for different metals.



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Explanation by the classical theory

The wave theory (or the classical electromagnetic theory) predicts (1) (that i_p increase with I) and contradicts (2) according to the wave theory, radiation should take much longer time to accumulation enough energy to, pull the electron from the surface. Also there should be no minimum energy (threshold frequency) for emission of photoelectron. If the incident light shines for a long enough time, it should be able to pull the electrons from the surface.

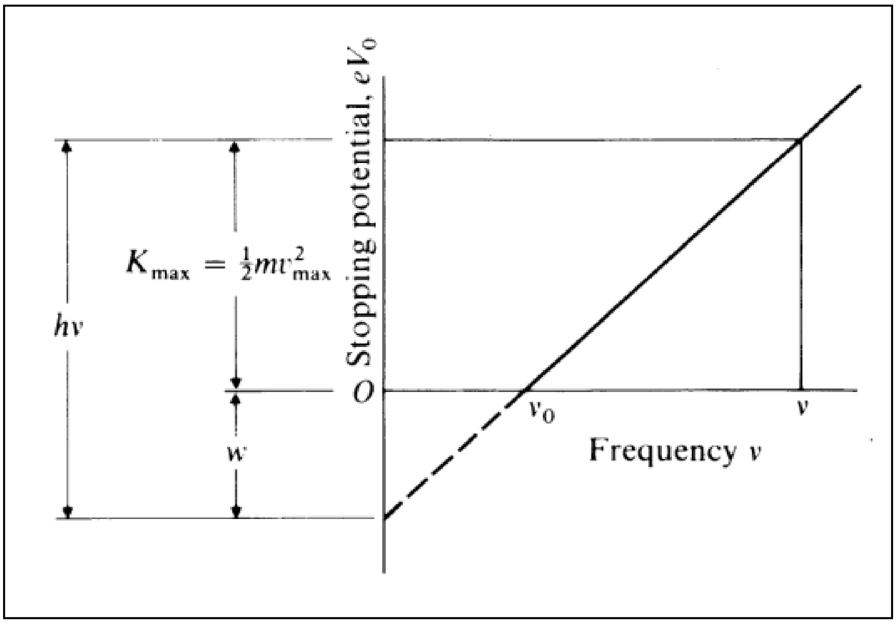
The classical theory contradicts points (4) and (5) but does not predict (6) at all.

Explanation by quantum theory

Plank assumed that electromagnetic radiation to be emitted or absorbed in bundles of size $h\nu$, where h is plank's constant, one could correctly predict the blackbody spectrum. Such a bundle of energy is called a quantum. the quantum hypothesis says that electromagnetic radiation of frequency ν incident on metallic surface consists of bundles of energy, if an electron absorbs a photon of energy $h\nu$, in order to escape from the metallic surface it uses up an amount of energy, w called the work function of the metal, while the rest of the energy (equal to $h\nu - w$) appears as kinetic energy k_{maxi} of the electron. Thus

$$k_{max} = h\nu - w$$

Comparison shows that h is the constant slope a, while –w is the intercept b, which is different for different metals. thus the quantum hypothesis has successfully explained(6),while (1) to (5) in the above listing follow very simply☹1) if the intensity of the beam increases, the number of photons in the beam striking the surface also increases, leading to an increase in photoelectron emission and hence in the current i_p . (2) either the electron absorbs the photon and is pulled out of the surface at once, or not at all. Thus there should be no time lag between absorption and emission.(3) according to Einstein equation for an electron to be just released from the surface . That is $k_{maxi}=0$, the photons must have a threshold energy ν_o given by $h\nu_o = w$,that is, an energy equal to the work function (or binding energy of the electron) of the surface of the metal ,from 4, 5 and Einstein equation, it is obvious that k_{maxi} is independent of I but depends on ν .



Example

Light of wavelength $\lambda = 5893\overset{o}{A}$ is incident on a potassium surface. The stopping potential for the emitted electrons is 0.36 volt. Calculate the maximum energy of the photoelectron, the work function and the threshold frequency.

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Example

A mercury arc is rated at 200 w. how many light quanta are emitted per second in radiation having wavelength of 6123 Å if the intensity of this line is 2% only. Assume that 50% of power is spent for radiation.

Example

A blue lamp emits light of mean wavelength of 4500 Å. The lamp is rated at 150 w and 8% of the energy appears as emitted light. How many photons are emitted by the lamp per second?

Example

Photoelectrons are emitted with a maximum speed of $7x10^5$ m/s from a metal surface when light frequency $8x10^{11}$ kHz falls on it. What is the threshold frequency of the metal?

Example

When violet light of =4000 Å strikes the anode of a photocell, a retarding potential of 0.4 volt is required to stop emission of electrons . calculate 1)light frequency 2)photon energy 3) work function 4) threshold energy 5) net energy after the electron leaves the surface.

Example

A certain metal has a threshold wavelength of 6525Å find the stopping potential when the metal is irradiated with

a) Monochromatic light having a wavelength of 4000Å

b) Light having twice the frequency and three times the intensity of that in (a) above.

c) If a material having doubled the work function were used, what would be the answers to (a) and (b).

Example

a certain metallic surface is illuminated by monochromatic light of variable wavelength . No photoelectron are emitted above a wavelength of 5000 Å. with an unknown wavelength a stopping potential of 3.1 volt is necessary to stop photoelectric current. Find the unknown wavelength.

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Example

Light of wavelength 2000 falls on an aluminum surface. in aluminum , 4.2 eV are required to remove an electron determine 1) K.E. of the fastest emitted photoelectron 2) K.E. of the slowest emitted electron 3) stopping potential 4)cut-off wavelength aluminum.

Homework

1) What is the energy, in electron volts, of a quantum of wavelength =5500Å.

2) In order for a normal eye to be sensitive to a visible light, it must receive 100 photons per second. Assuming that the wavelength of the visible light is 5550Å, how many watts of power at the threshold are receive by the eye.

3) Light of wavelength 4350Å is incident on a sodium surface for which the threshold wavelength of the photoelectrons is 5420Å. Calculate the work function in electron volts, the stopping potential, and the maximum velocity of the photoelectrons emitted.

4) When light of wavelength 3132 Å falls on a cesium surface, a photoelectron is emitted for which the stopping potential is 1.98 volts. Calculate the maximum energy of the photoelectron, the work function and the threshold frequency.

5) a beam of light of wavelength of wavelength 5550 Å strikes a metal surface for which the threshold is 7320 Å calculate the maximum kinetic energy of the emitted electron and the stopping potential.

6) The work function of tungsten is 4.53 eV. If ultraviolet light of wavelength 1500 Å is incident on this surface, does it cause photoelectron emission? If so what is the kinetic energy of the emitted electron.

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استاذ المادة
ا.م.د. علي احمد يوسف
قسم الفيزياء
الدراسات الصباحية