

## INTRODUCTION

The first developments of quantum mechanics are related to the experimental data recorded on

- a- **Blackbody radiation** spectra
- b- The **photoelectric effect** and **Compton effect**
- c- The **spectral lines** emitted by **hydrogen**

One could find out that the results of those experiments can be explained by accepting "*the postulate*":  
The amount of energy transferred in "fundamental interactions" is a multiple of an "energy quantum"

$$\text{Transferred energy} = m \cdot \epsilon \quad m = 1, 2, \dots \quad (1)$$

" $\epsilon$ " is the amount of energy contained in an "energy quantum"

**Note:** There is no such type of restriction in the classical physics (i.e. any amount of energy can be exchanged). So, the energy is a continuous parameter in classical mechanics but it is a discrete parameter in quantum mechanics.

## 1. BLACKBODY RADIATION

-When the temperature of a "black" object overcomes a certain value it starts to appear reddish; i.e. it emits a visible radiation that appears red for us. A further increase of temperature changes this colour to almost white. As the characteristics of this type of radiation depend only on the object temperature, one has labelled it as thermal radiation (ex. stove heating element).

*The "colour" of thermal radiation depends essentially on the temperature of its source.*

- The spectral analysis of *recorded spectra*, showed that the *energy of thermal radiation is distributed over a large range of E&M wavelengths*. The visible light constitutes only a small part of thermal radiation (see fig 1). To explain the origin of this radiation, one introduced a physical model based on *a big number of oscillators* (molecular or atomic oscillators) at *source of radiation*. *Each of them oscillates at a given frequency "f" and emits an E&M wave at same frequency (or wavelength  $\lambda = c/f$ ); this wave becomes part of thermal radiation*. Theoretical calculations refer to the *exchange of energy* between *molecular oscillators at source* and the *E&M travelling waves that constitute the thermal radiation*.

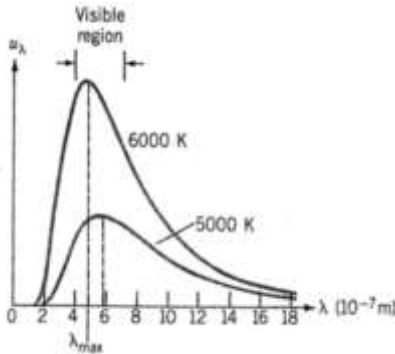


Fig 1

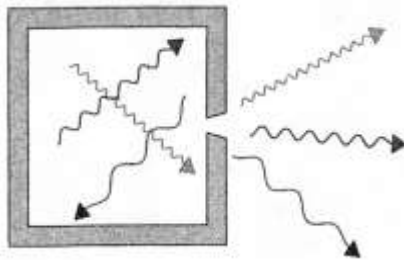


Fig 2

- The *molecular oscillator* emits an E&M wave at the frequency of its oscillations. The *number of molecular oscillators* that oscillate at a given *frequency* depends on the *temperature of source*. At a fixed temperature, there is a *specific distribution* for the *number of molecular oscillators* versus *frequency*. If the *temperature of source is constant*, there is *equilibrium* and this *distributions remains unchanged*. The same distribution is transferred to the emitted thermal radiation. One records and analyzes the *thermal radiation* emitted by a "blackbody" kept at a fixed temperature and uses it to get the distribution of energy through wavelengths (see fig.1) of radiation.

- A closed cavity with only a tiny opening (see fig. 2) is a good experimental set up for the blackbody model. The **black body** is an **ideal model** that absorbs all radiations incident on it. A *radiation wavelet that enters the cavity has very low probability to get out and, at the end, get absorbed by cavity walls*. One heats the cavity walls and keeps them at a constant temperature **T**. The radiation inside the cavity, i.e. the **blackbody radiation**, is a *thermal radiation at same constant temperature T*. One analyzes a small amount (see fig.2) of this radiation allowed to escape out of cavity.

-The molecular oscillators at cavity walls emit E&M wavelets and after a short interval of time, an equilibrium is established in *energy exchange* between the "sources at walls" and the *radiation* inside cavity. After this moment, the *energy density*  $\mathbf{u}(\mathbf{T})$  [J/m<sup>3</sup>] of radiation and its *distribution*  $\mathbf{u}_\lambda(\mathbf{T})$  through different wavelengths remain constant. The amount of radiation energy in interval  $\lambda, \lambda+\Delta\lambda$  is  $\Delta u = \mathbf{u}_\lambda * \Delta\lambda$  where one has **defined**  $\mathbf{u}_\lambda(\mathbf{T})$  as

$$u_\lambda(T) = \frac{d}{d\lambda} u(T) \quad (2)$$

One measures this *spectral energy density*  $\mathbf{u}_\lambda(\mathbf{T})$  [J/m<sup>4</sup>] by recording and analyzing the spectrum of the samples of radiation taken out of the opening (fig 2). So, one studies the thermal radiation inside the cavity by referring to this representative sample.

If one knows function  $\mathbf{u}(\mathbf{T})_\lambda$  (i.e. graph in fig#1), one can calculate the *density of radiation energy* inside cavity as

$$u(T) = \int_{\lambda_{\min}}^{\infty} u_\lambda(T) d\lambda \quad (3)$$

Note that the expression (3) is equal to the area under the graphs  $\mathbf{u}(\mathbf{T})_\lambda = \mathbf{f}(\lambda)$  in fig 1.

-The experiments showed that the blackbody radiation spectra:

- a) do not contain any narrow spikes; they are continuous and have a wide maximum;
- b) depend only on the temperature in cavity. When temperature is raised:
  - b.1- the **energy density**  $\mathbf{u}(\mathbf{T})$  increases (graph shifted up) and
  - b.2 - the peak position shifts versus shorter  $\lambda$ .

- Except for some formulas that fit the infrared part (found by Wien and Rayleigh -Jeans), by the end of 19<sup>th</sup> century, the physicists could not **develop a classical model** that would describe **all the experimental features** of the whole spectrum of blackbody radiation (i.e. all parts of the graph in fig.1).

\*The **Wien's first law** gives the relation between the *position of maximum* and the *temperature*;

$$\lambda_{\max} * T = 2.898 * 10^{-3} [mK] \quad (4)$$

*wavelength measured in meters and temperature measured in degrees Kelvin (273+C<sup>0</sup>)*

\*\* The **Wien's second (radiation) law** gives the expression

$$u_\lambda(T) = A * \lambda^{-5} e^{-B/\lambda T} \quad A, B \text{ two constants} \quad (5)$$

that fits well with experimental results in the **near infrared spectrum** (0.7÷6  $\mu\text{m}$  or 700÷6000nm).

\*\*\* The **Rayleigh- Jeans law** gives the expression

$$u_\lambda(T) = 8\pi k * T * \lambda^{-4} \quad (6)$$

that fits well with recorded data for the **far infrared region** (>15 $\mu\text{m}$  or >150\*10<sup>-7</sup>m).

\*\*\*\* There was not even any empirical formula that would provide the part of spectrum  $\lambda < \lambda_{\max}$ .

This is known as the "**ultraviolet catastrophe**" in physics. Max Planck resolved this situation.

-Like other physicists, Max Planck applied the thermodynamic principle of *maximum entropy* for the *equilibrium of system constituted by oscillators in the walls and the radiation* inside cavity. When referring to the sources of radiation " i.e. **wall oscillators** ", he considered two **mathematical** possibilities:

- a) the molecular oscillator can exchange *any amount* of energy (i.e. it is a *continuous parameter*) with radiation.
- b) the molecular oscillator can exchange *only multiples* of a **quantum of energy** " $\epsilon$ " with radiation.

As the first hypothesis did not work, he checked the second. Assuming that this minimum amount of energy " $\epsilon$ " relates to the frequency "f" of molecule oscillations (and emitted wavelet) as

$$\epsilon = h * f; \text{ where } f = c / \lambda \tag{7}$$

he got the expression

$$u_{\lambda}(T) = \frac{8\pi hc \lambda^{-5}}{e^{hc/\lambda kT} - 1} \tag{8}$$

The expression (8) is known as **Planck's radiation law**. It yields correctly the *complete spectrum* of thermal radiation for the following value of " $h$ " (known as *Planck constant* )

$$h = 6.626 * 10^{-34} \text{ J * s} \tag{9}$$

Note that expression (8) transforms to (5,6) for  $\lambda$  values in infrared region.

As it can exchange only by multiples of " $hf$ ", the **energy of a quantum oscillator** (molecule or atom) should have a discrete structure, i.e. the energy of oscillator in its  $n^{\text{th}}$  "level" would be

$$E_n = E_0 + nhf \quad n=1,2,3... \tag{10}$$

$E_0$  stands for minimal (or fundamental) level of energy

In 1900 Planck introduced the idea of the quantization for the energy levels of **matter** only as a mathematical artifice.

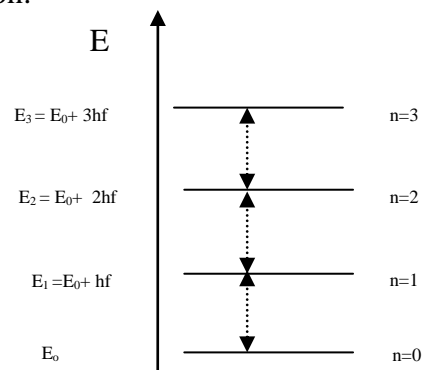


Fig.3 Energy levels of a quantum oscillator

- In 1906, Albert Einstein applied **quantum** model for the **energy of light** to explain the characteristics of photoelectric effect. This way the quantum model was introduced in studies of matter and E.M. fields.

Essentially, this development means that a *quantum oscillator*(a physic's model used for matter or radiation):

- a) Has a discrete set of energy values.
- b) The 'spacing' between the *energy levels* depends on the *oscillator frequency "f"*.
- c) It can absorb or emit only portions of energy which are multiples of energy quantum  $\epsilon = hf$ .

## 2.THE PHOTOELECTRIC EFFECT

- By the end of 19<sup>th</sup> century J.J.Thomson discovered that when a beam of **visible light** illuminates an object covered by a layer of alkali metals (Na, Ka, Cs), this layer can become positively charged and this happens because many free *electrons are expelled* from the layer.

**The photoelectric effect is the emission of electrons by a metal when a beam of light illuminates it.**

- Figure 4 presents the basic scheme used for the study of photoelectric effect characteristics. A beam of **monochromatic** light illuminates the plate P covered by an alkali metal layer. The *photoelectrons* that are ejected from the plate P get attracted by a metallic cylinder C **initially** connected to positive terminal (shown by dashed lines in fig.4) of a DC source. Once inside C electrode, the electrons move through the electric circuit and produce a current<sup>1</sup> measured by the ammeter "A".

<sup>1</sup> The current magnitude is proportional to the number of electric charges (electrons) passing the wire section in 1 sec.

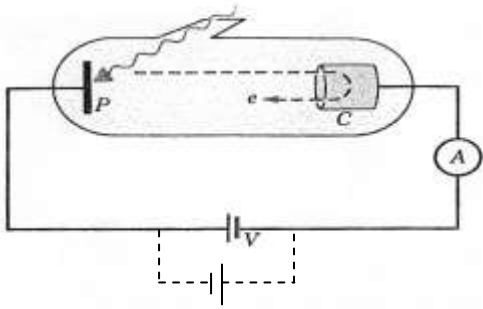
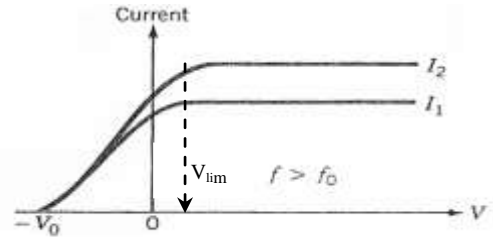


Fig 4



For  $V > 0$  on electrode C, the current in circuit increases if the intensity of illuminating beam "I" increases. However, the value of stopping potential ( $V_0 < 0$ ) does not depend on the intensity of illuminating beam.

Fig 5

The plate P and the cylinder C are enclosed inside a vacuum glass ampoule to avoid the collisions of photoelectrons with air molecules. The graphs in figure 5 present the current for different values of potential difference applied between C and P electrodes. These graphs show that:

- 1- When the voltage of **collector** C is positive and larger than a certain value  $V_{lim}$ , the current in ammeter is constant. This means that for  $V = V_{lim}$  the electrode C collects *all ejected electrons*.
- 2- When the potential in collector C is positive but lower than  $V_{lim}$ , a number of emitted electrons ejected out of plate P cannot reach the collector C; the current in ammeter decreases.
- 3- When the potential V is negative, the electrons are repelled from C and only the most energetic ones can reach the collector, get into it and produce a current. When the negative potential in C reaches the value  $-V_0$ , even the electrons emitted at maximum kinetic energy may **get till but not into** C.

- The classic wave model assumes that the **light wave** would transfer the energy to a free electron of metal layer in a **continuous way** and it **would take some time** so that this electron can gather enough energy to get out of metal and get attracted or repelled from the potential V at collector C.

The classic model predict correctly:

- a) The **increase of photocurrent** when the incident **light intensity increases** ( $I_2 > I_1$ , see fig.5).
- b) The **maximum speed** of emitted photo-electrons based on energy conservation from relation

$$K_{max} = \frac{1}{2} m v_{max}^2 = e V_0 \quad (11)$$

$e = 1.602 \cdot 10^{-19}$  Coulomb (magnitude of electron charge) and  $V_0$  [V] is the **stopping electric potential** that does not allow even the most energetic electrons to get into collector C.

The classic model do not fit to the experimental observations while it predicts that the "  $e^-$  emission " "

- c) should start only at a *certain time after* starting illumination of metal.  
Experiments show the opposite, i.e. **instantaneous emission of "photoelectrons"** or no emission at all.
- d) should happen for any value of wavelength of incident radiation. The experiments show that: *always*, there is a  $\lambda_{max}$  such that for  $\lambda_{incident} > \lambda_{max}$  there is **no emitted electrons**.
- e) should not happen if the intensity of incident light beam  $I_{light} < I_{thr}$  where  $I_{thr}$  would be a *threshold intensity value*. The measurements show that :  
Provided that the light *wavelength*  $\lambda < \lambda_{max}$  (or *frequency*  $f > f_{min}$ ) the photoelectrons are emitted for **any intensity of incident light**; so, **there is no** such a  $I_{thr}$  value.

-The points c, d, e showed a discrepancy of experimental results to classical wave model predictions. Albert Einstein resolved this situation by postulating that:

**The radiation behaves as a collection of discrete energy quanta, each of magnitude**

$$\varepsilon = h * f \quad (12)$$

*h is the Planck constant and f the frequency of radiation*

Later on, after twenty years, physicist named these **light particles** as **photons**.

- A. Einstein proposed the following **quantum model** for the photoelectric effect;

a) At **each single shot**(when this happens) **on a free electron in metal**, a single photon gives up all its energy "ε" (and disappears) to the electron. This electron may be **ejected instantaneously** from metal if the received energy is larger than work function  $\phi^2$ . In general, before leaving the metal, this electron loses an amount of this energy due to possible interactions inside the metal. So, the kinetic energy K of ejected photoelectrons obeys to the condition

$$K \leq \varepsilon - \phi \quad \text{or} \quad K + \phi \leq \varepsilon \quad (13)$$

b) The **maximum kinetic energy**  $K_{max}$  corresponds to "photoelectrons" that do not get any interaction inside the metal. For those electrons  $K \equiv K_{max} = \varepsilon - \phi$  and this brings to following relations

$$\varepsilon = \phi + K_{max} \quad \text{or} \quad h * f = \phi + \frac{1}{2} m v_{max}^2 \quad (14)$$

c) Relations (13,14) tell that there is a **threshold frequency** " $f_{min} \equiv f_0$ " for "e-" emission. One can find it by using the condition  $K \geq 0$ . The minimum frequency of incident light must fit to  $K=0$ ; i.e.  $\varepsilon_{min} = \phi$

$$h * f_0 = \phi \quad (15)$$

For  $f \leq f_0$  the electrons cannot leave the plate P because the amount of transferred energy  $\varepsilon=hf < \phi$ .

d) Based on (11,14,15), one can get the value of the stopping potential  $V_0$  from relation

$$K_{Max} = eV_0 = hf - hf_0 \quad \text{and} \quad V_0 = (h/e) * (f - f_0) \quad (16)$$

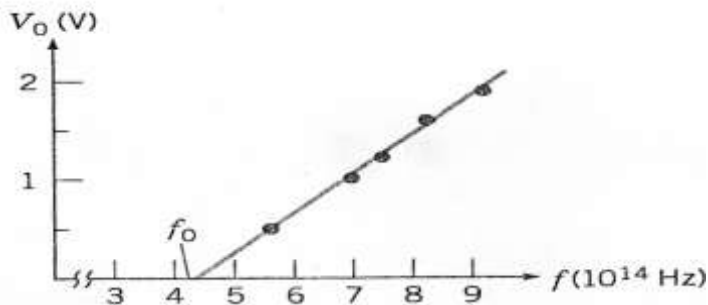


Fig. 6 Graph relating the measured stopping potential values to different f-values of incident light

<sup>2</sup> the necessary minimum of energy to extract an electron from the surface of the material.

### 3.THE COMPTON EFFECT

Einstein introduced the *photon* , i.e. the concept of *quantum* into *visible light* at 1905, but it took about twenty years for the quantum model of light to be officially accepted.

- In 1923,A.H.Compton published the spectra of *x- radiation* scattered by graphite crystals. These spectra contain **two bands**; One at **same** wavelength as that of the incident radiation ( $\lambda= 0.071\text{nm}$ ) and another one with  $\lambda' > \lambda$  (see fig 7). He noted that the wavelength  $\lambda'$  of the second band depends on the scattering angle " $\theta$ " (fig.8) but not on the constituency of the target material. Compton explained the **results** of his experiments by modelling X-rays as a set of photons that behave as particles with linear momentum.

The *classic model* explains the origin of the first band as follows " the electrical charges in the sample oscillate at the same frequency as the wave of incident radiation and emit a wave at same frequency ".

But it cannot not explain the presence of the second band ( $\lambda'$ ) in scattered radiation spectra.

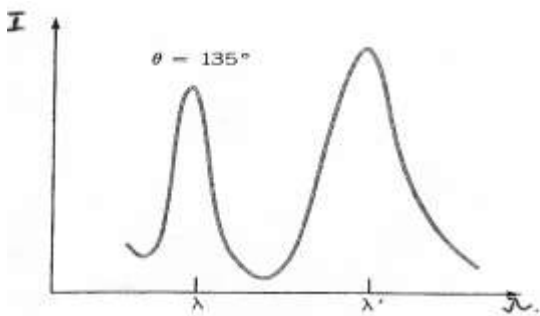


Fig 7

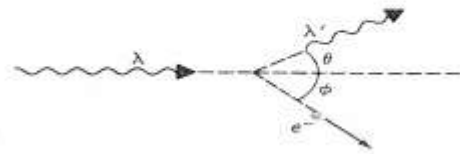


Fig 8

- Compton explained the presence of the second band by modelling incident X-radiation as a beam of "**X-photons**" i.e. *quantum particles*. He considered the collision of two "*single particles*" (one X-photon and one "*free*" electron at external shell of carbon atom) and performed calculations in a **relativistic frame**.

The energy of incident X-ray photon is much larger than the **binding energy of electrons in the external shells** of C-atoms of graphite. So, during the interaction with X-ray photons, a **loosely tied electron** in the target can be modelled as "**a free electron** ".

As the energy of an incident X-photon is  $E = h*f$  and its *rest mass* is **zero**, one can get the *magnitude* of

its **linear momentum** as  $E^2 = p^2c^2 + (m_0c^2)^2 \rightarrow E = p*c \rightarrow p = E/c = \frac{h*f}{c} = \frac{h}{\lambda}$  (17)

By applying the *principle of energy conservation* for the collision between an **electron initially at rest** and an incident X-photon (see fig.8), one get

$$(E_{el} + E_{ph})_{before\_coll} = (E_{el} + E_{ph})_{after\_coll} \rightarrow m_0^{el}c^2 + \frac{hc}{\lambda} = m_0^{el}c^2 + K^{el} + \frac{hc}{\lambda'} \quad (18)$$

By cancelling the rest energy of electron on both sides of (18) one get its kinetic energy after collision as

$$\frac{hc}{\lambda} = \frac{hc}{\lambda'} + K^{el} \quad \text{and} \quad K^{el} = \frac{hc}{\lambda} - \frac{hc}{\lambda'} \quad (19)$$

The conservation of **linear momentum** for the set (*photon - electron*) before and after collision tells that

$$\vec{p}_{photon} = \vec{p}'_{photon} + \vec{p}_{electron} \quad (20)$$

As the magnitudes are " $p_{photon} = h/\lambda$ " and " $p_{electron}$ ", by referring to the directions " $\theta$ " for the deflected X-photon and " $\varphi$ " for deflected electron(see Fig.8), the projection of vector relation (20) on axes gives

$$\begin{aligned} O_x \text{ - axe; } \frac{h}{\lambda} &= \frac{h}{\lambda'} \cos\theta + p_{electron} \cos\varphi \text{ - or - } p_{electron} \cos\varphi = \frac{h}{\lambda} - \frac{h}{\lambda'} \cos\theta \\ O_y \text{; - axe; } 0 &= \frac{h}{\lambda'} \sin\theta - p_{electron} \sin\varphi \text{ - or - } p_{electron} \sin\varphi = \frac{h}{\lambda'} \sin\theta \end{aligned} \quad (21)$$

One notes  $p_{electron} \equiv p$ , takes the squares of both sides in relations (21), add them side by side, factorize  $p^2$  and substitutes  $\cos^2\varphi + \sin^2\varphi = 1$  to the left side. Then, one factorize  $(h^2/\lambda'^2)$  to the right side and get

$$\begin{aligned} p^2 &= \left(\frac{h}{\lambda} - \frac{h}{\lambda'} \cos\theta\right)^2 + \frac{h^2}{\lambda'^2} \sin^2\theta = \frac{h^2}{\lambda^2} - 2\frac{h}{\lambda} \frac{h}{\lambda'} \cos\theta + \frac{h^2}{\lambda'^2} \cos^2\theta + \frac{h^2}{\lambda'^2} \sin^2\theta = \frac{h^2}{\lambda^2} + \frac{h^2}{\lambda'^2} - 2\frac{h}{\lambda} \frac{h}{\lambda'} \cos\theta \\ p^2 &= h^2 \left(\frac{1}{\lambda^2} + \frac{1}{\lambda'^2} - 2\frac{1}{\lambda\lambda'} \cos\theta\right) \end{aligned} \quad (22)$$

From relation  $E^2 = (\mathbf{K} + \mathbf{E}_0)^2 = \mathbf{K}^2 + 2\mathbf{K}\mathbf{E}_0 + \mathbf{E}_0^2 = \mathbf{E}_0^2 + (\mathbf{p}\mathbf{c})^2$ , one get  $\mathbf{p}^2\mathbf{c}^2 = \mathbf{K}^2 + 2\mathbf{K}\mathbf{E}_0$  and by using (19) rewrites it as

$$p^2 = \frac{1}{c^2} (\mathbf{K}^2 + 2\mathbf{K}\mathbf{E}_0) = \frac{1}{c^2} \left[ \left(\frac{hc}{\lambda} - \frac{hc}{\lambda'}\right)^2 + 2\left(\frac{hc}{\lambda} - \frac{hc}{\lambda'}\right) m_0^{el} c^2 \right] = \frac{1}{c^2} \left[ c^2 h^2 \left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right)^2 + 2c^2 h^2 \left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) \frac{m_0^{el} c}{h} \right]$$

and next

$$p^2 = h^2 \left[ \left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right)^2 + 2\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) \frac{m_0^{el} c^2}{h} \right] = h^2 \left[ \frac{1}{\lambda^2} + \frac{1}{\lambda'^2} - 2\frac{1}{\lambda\lambda'} + 2\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) \frac{m_0^{el} c}{h} \right] \quad (23)$$

By equalizing the right sides of expressions (22, 23) one gets

$$\frac{1}{\lambda^2} + \frac{1}{\lambda'^2} - 2\frac{1}{\lambda\lambda'} \cos\theta = \frac{1}{\lambda^2} + \frac{1}{\lambda'^2} - 2\frac{1}{\lambda\lambda'} + 2\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) \frac{m_0^{el} c}{h} \quad \text{or}$$

$$2\frac{1}{\lambda\lambda'} - 2\frac{1}{\lambda\lambda'} \cos\theta = 2\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) \frac{m_0^{el} c}{h} \text{ which can be written as } \frac{1}{\lambda\lambda'} (1 - \cos\theta) = \left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) \frac{m_0^{el} c}{h}$$

and after multiplying both sides by  $\lambda\lambda'$  one get

$$\lambda' - \lambda = \left(\frac{h}{m_0^{el} c}\right) (1 - \cos\theta) \quad (24)$$

The quantity  $(h/m_0^{el} c) = 0.00243 \text{ nm}$  is known as Compton wavelength.

**Remember:** Maxwell theory (*classical physics*) considers that x-rays are E.M. waves and it **cannot explain** the presence of a  $\lambda'$ - band in scattered radiation. In the quantum model, X-rays are a beam of **photons** each **containing** the **energy**  $E = hc/\lambda$  and **linear momentum**  $p = h/\lambda$ .

The quantum model explains the presence of a  $\lambda'$ - component in scattered radiation and provides an expression that fits to experimental recordings.

## 4.THE LINE SPECTRA

- As explained in first section, hot bodies emit a thermal radiation with *continuous spectrum*. However, the spectra emitted by a **rarefied gas** under an electrical discharge (or gas at very high temperature) contain sharp spectral lines. The scientists could realise that **each chemical element emits a set of characteristic spectral lines** that can be used to identify the presence of this element in a sample.

The classical physics models cannot find explanation for the presence of sharp lines in those spectra.

- The **visible spectrum** emitted by rarefied hydrogen under an electrical discharge contains four lines at

$$410.12, 434.01, 486.07 \text{ and } 656.21 \text{ nm.}$$

The study of this spectrum started by finding an *empirical* expression, the **Balmer formula**

$$\lambda_m = 364.56 \frac{m^2}{m^2 - 4}; \rightarrow m = 3,4,5,6 \quad (25)$$

which produces the four measured  $\lambda$ -values for shown m- values.

- Niels Bohr built the first physical model that offered an explanation for the origin of line spectra from hydrogen atom. In this model, Bohr **assumed** that there are only some circular "**allowed orbits**" for the revolution of the single electron around the nucleus of H-atom(fig 9).

*This unacceptable assumption for classical physics produced a quantified expression for the energy (expression 26) and allowed to derive the wavelengths of hydrogen spectra lines.* Bohr's model gives good results for all **single electron systems** such as **H, He+, Li++** by replacing the nuclear charge of hydrogen (+e) to (+Ze). The Bohr's expression for the energy levels of *one electron systems* is

$$E_n = -\frac{13.6 * Z^2}{n^2} eV; \_ n = 1,2,3... \infty \quad (26)$$

-Fig. 10 presents the energy level diagram for hydrogen (**Z=1**). Each *state* of **system electron - nucleus** (and *orbit* of electron) is defined by the **integer n (principal quantum number)**. One says that the atom is in its **ground state (n =1)** when this system has the minimum energy value ; otherwise the atom is in an **excited state (n=2,3,4..)**. One may calculate the energy value in different levels by (26) and find out that  **$E_1 = -13.6eV$ ,  $E_2 = -13.6/2^2 = -3.4eV$ ,  $E_3 = -13.6/3^2 = -1.51eV$**  and so on. The **energy zero** corresponds to the "**largest orbit**" ( $n = \infty$  i.e.  $E_\infty = 0eV$  for unbound e-). For each **bound state**, the electron (or more precisely **H-system**) has a **negative energy**. In normal conditions, a bound electron tends to be in the lower level of energy which corresponds to the *most stable configuration* of system. So, for a collection of many atoms, **in normal conditions**, majority of electrons *populate the lowest levels of energy*.

-A bound *electron can be raised to a higher energy level by **absorbing a photon only if the photon energy is exactly equal** to the energy difference between two states of the system (nucleus-electron).*

Once in an **excited state (n >1)**, the atom would tend to fall to a lower energy level by **emitting** a photon. This type of transition is at the origin of any line that appears in an **emission spectrum**. If the energy of absorbed photon is equal or **larger** than 13.6eV (**ionization energy of H-atom**) the electron is **ejected out of the atom**. It becomes a free electron for which the energy changes in continuous way. *Un electron has a discrete energy if it is bound and continuous energy if it is unbound.* So, an electron can receive or give energy only in discrete amounts during a transition between two bound states but this restriction does not apply for a transition to an unbound state or for a free electron.



- Actually, **Balmer's emission series** correspond to transitions of electron (i.e. H- system) from higher energy levels ( $n=3,4,5,\dots$ ) to the level with  $n = 2$ . The emitted photons during those transitions produce the four spectral lines in the visible spectrum of hydrogen. The transitions started from levels with  $n=2,3,4,\dots$  to the level with  $n = 1$  form the **Lyman** emission series (all lines in UV); those from  $n=4,5,6,\dots$  to the level with  $n=3$  form the **Paschen** (all lines in IR) series.

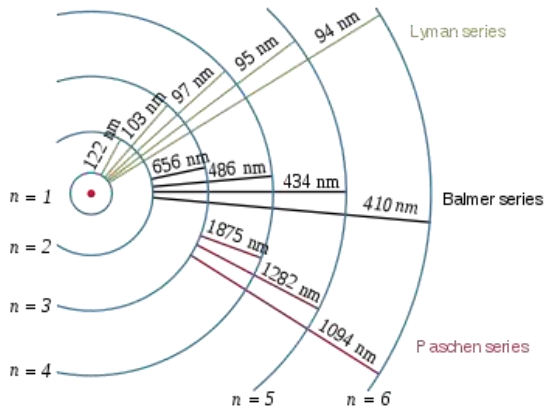
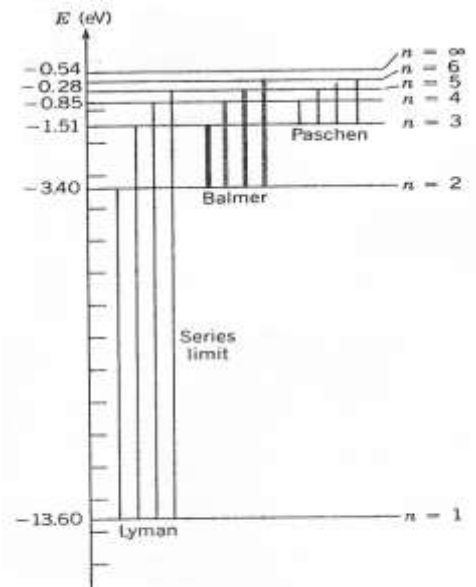


Fig.9



The energy level diagram for hydrogen. Light is emitted or absorbed when an electron makes a transition between two levels.

Fig.10