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**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 found 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"*

$$\text{Transferred energy} = m^* \varepsilon \qquad m = 1, 2 \qquad (1)$$

"$\varepsilon$" is the amount of energy contained in "one energy quantum"

There is no such type of restriction in 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 objects overcomes a certain value they starts to appears *reddish*. This means that they emit a visible radiation that *appears red* for us (like radiation emitted by a stove element). A further increase of temperature can change their colour to almost white. As the characteristics of this radiation depend only on the ***temperature*** of its source, one has labelled it as **thermal radiation**.

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

- The analysis of recorded *spectra*, showed that the *energy of thermal radiation is distributed over a wide range of **E&M** wavelengths*. The visible light constitutes only a small part of thermal radiation spectrum (see fig 1). To explain the origin of this radiation, one introduced a physical model based on ***a large 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 $\lambda = c/f$ );* ***this waves become part*** of ***thermal radiation.*** The theoretical calculations refer to the ***exchange*** *of energy* between *molecular oscillators at source* and the E&M *waves that constitute the thermal radiation.*

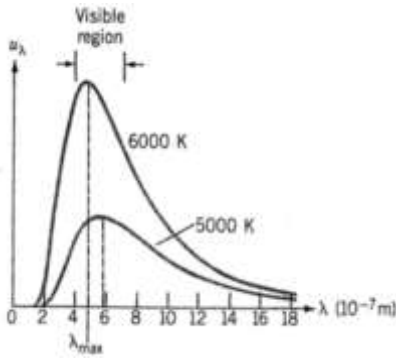



Fig 1

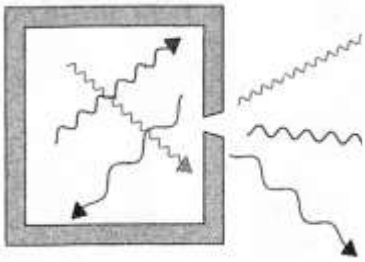


Fig 2

- A *molecular oscillator* emits a E&M wave at the frequency of its oscillations and the *number* of *oscillators* that oscillate at a given *frequency* depends on the temperature of source. At each temperature, there is a ***specific distribution*** for the *relative 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 spectrum of *thermal radiation* emitted by a *"blackbody"* kept at a fixed temperature. This spectrum gives the distribution of energy through wavelengths (fig.1).

- The **black body** is an **ideal model** that absorbs all radiations incident on it. A closed cavity with only a tiny opening (see fig. 2) is a good experimental set up for the blackbody model. *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 are the sources of E&M wavelets inside cavity. After a short interval of time, an equilibrium is established in *energy exchange* between the "*sources at walls*" and

the *radiation* inside cavity. After that, the *energy density* **u(T)**[J/m$^3$] of radiation and its *distribution* $\mathbf{u}_\lambda$ **(T)** through different wavelengths remain constant. The amount of radiation energy inside interval $\lambda, \lambda+\Delta\lambda$ is $\Delta u = \mathbf{u}_\lambda * \Delta\lambda$ where one has **defined** $\mathbf{u}_\lambda$ **(T)** as

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

One measures this *spectral energy density* $\mathbf{u}_\lambda$ **(T)** [J/m$^4$] by recording and analyzing the spectrum of the samples of radiation taken out of the opening(fig 2). So, one studies the characteristics of thermal radiation inside the cavity by referring to this representative sample. If one knows function $\mathbf{u(T)}_\lambda$ (i.e. graph in fig#1), one can calculate the *density of radiation energy* inside cavity as

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

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

-The experiments showed that the ***blackbody radiation spectra***:

a) are ***continuous*** and have a ***wide maximum*** ; they do not contain any narrow spikes.
b) depend only on the temperature in cavity. When temperature is increased:

- the ***energy density u(T)*** increases(*graph shifts up*) <u>*and*</u> - the maximum $\lambda_{max}$ shifts versus shorter $\lambda$.

- Wien and Rayleigh-Jeans found empirical formulas that fit to the infrared part of spectrum in fig.#1. But, until the end of 19$^{th}$ century, the physicists could not ***develop a classical model*** that would predict ***the experimental features*** of the whole spectrum of blackbody radiation.

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

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

*wavelength measured in meters and temperature measured in degrees Kelvin(273+C$^0$)*

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

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

that fits well with experimental results in the **near infrared spectrum** (*0.7÷6 μm or 700÷6000nm*).

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

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

that fits well with recorded data for the ***far infrared region*** ( >15μm or >150*10$^{-7}$*m*).

**** There was not even any empirical formula that would provide the part of spectrum $\lambda < \lambda_{max}$. This situation is known as the " ***ultraviolet catastrophe*** ". Max Planck resolved this situation.

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

a) a molecular oscillator can exchange *any amount* of energy(a *continuous parameter*) with radiation.
b) a molecular oscillator can exchange *only multiples* of a ***quantum of energy*** "**ε**" with radiation.

As the first hypothesis did not work, he checked the second. Assuming that this minimum amount of energy "**ε**" relates to the <u>*frequency*</u> *" f "* *of* <u>*molecule oscillations*</u> (*and emitted wavelet*) as

$$\varepsilon = h * f; _ where _ f = c/\lambda \qquad (7)$$

he got the expression

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

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* )

$$h = 6.626*10^{-34}\, J*s \qquad (9)$$

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

*As it can change 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 $n^{th}$ "level" would be*

$$E_n = E_0 + nhf \quad \text{n=1,2,3...} \qquad (10)$$

$E_0$ 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.*

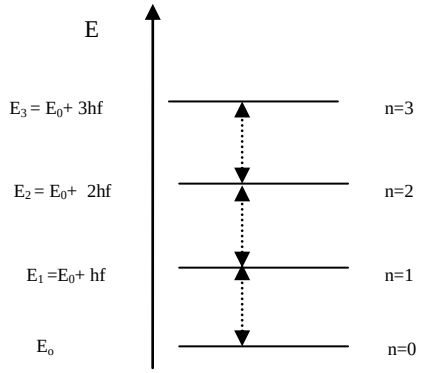



Fig.3 Energy levels of a quantum oscillator

- In 1906, A. 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.

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 $\boldsymbol{\varepsilon} = \boldsymbol{hf}$.

## 2.THE PHOTOELECTRIC EFFECT

- By the end of 19th 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 get 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 which is ***initially*** connected to the positive terminal (shown by dashed lines in fig.4) of a DC source. Once inside "C" electrode, the electrons move through the closed electric circuit and produce a current[1] measured by the ammeter "A".

Fig 4

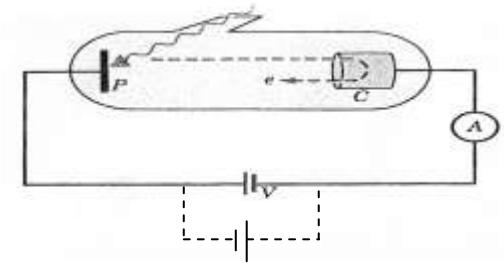
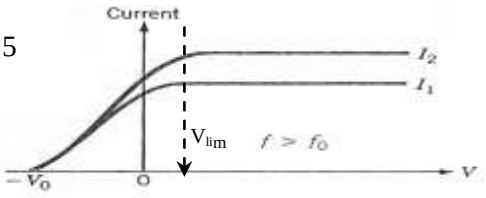



Fig 5




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.

[1] The current magnitude is proportional to the number of electric charges (electrons) passing the wire section in 1 sec.

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 evolution of 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 $V \geq V_{lim}$ the electrode C collects *all ejected electrons.*
2- If 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 and the current in ammeter decreases.
3- If the potential V is negative, the electrons are repelled from C and only the most energetic ones that can get into collector 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; next, it can get attracted or repealed from the potential V at collector C. This classic physics model based on *light as a wave* 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

$$K_{\max} = \frac{1}{2} m \upsilon_{\max}^2 = eV_0 \qquad (11)$$

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

But, the classic model predicts "incorrectly" that the " $e^-$ *emission " :*

c) should start only at *a certain time after* starting the illumination of metal layer.

Experiments show ***instantaneous emission*** *of* ***"photoelectrons"*** or no emission at all.

d) should happen for ***any value of wavelength*** of incident radiation.

Experiments show that ***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 $I_{light} < I_{thr}$ where $I_{thr}$ is a *threshold value.*

Experiments show that if the light *wavelength* $\lambda < \lambda_{max}$ (*or frequency* $f > f_{min}$) there is emission of photoelectrons for ***any intensity of incident light;*** so, **there is no** such a $I_{thr}$ value**.**

-The points c, d, e proved 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***

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

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

Later on, after twenty years, physicist named these ***light energy quanta*** 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*** *if the received energy is larger than work function* $\varphi^2$ *of metal. 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*

[2] *the necessary minimum of energy to extract an electron from the surface of the material.*

$$K \leq \varepsilon - \varphi \quad or \quad K + \varphi \leq \varepsilon \tag{13}$$

*b) The* ***maximum kinetic energy*** $K_{max}$ *corresponds to "photoelectrons" that have no interaction inside the metal.* For those electrons $K \equiv K_{max} = \varepsilon - \varphi$ and this brings to following relations

$$\varepsilon = \varphi + K_{max} \quad or \quad h * f = \varphi + \frac{1}{2} m \upsilon_{\max}^2 \tag{14}$$

*c) Relations (13,14) tell that there is a* ***threshold frequency*** *"* $f_{min} \equiv \boldsymbol{f_0}$ *" 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.* $\varepsilon_{min} = \varphi$

$$h * f_0 = \varphi \tag{15}$$

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

*d) Based on relations (11,14,15), one can get the value of the* ***stopping potential*** $\boldsymbol{V_0}$ *from relation*

$$K_{max} = eV_0 = hf - hf_0 \quad and \quad V_0 = \left(\frac{h}{e}\right) * (f - f_0) \tag{16}$$

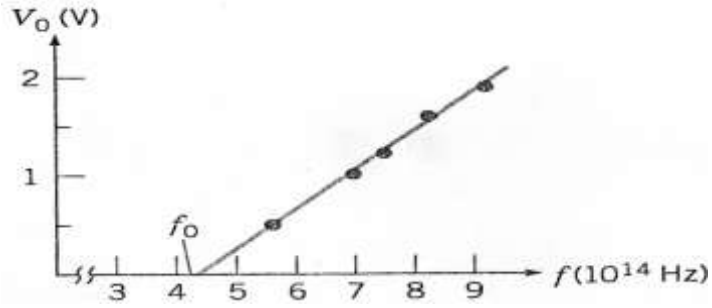



Fig. 6 Graph relating the stopping potential to the frequency of incident light

## 3.THE COMPTON EFFECT

- 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 ($\boldsymbol{\lambda}$= 0.071nm) *and another one with* $\boldsymbol{\lambda' > \lambda}$ (see fig 7). He noted that *the* ***wavelength*** $\boldsymbol{\lambda'}$ *of the second band* ***depends on*** *the scattering* ***angle*** *"θ" (fig.8) but* ***not on the constituency*** *of the target material*.

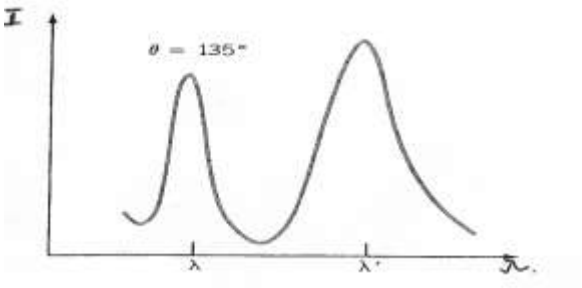



Fig 7

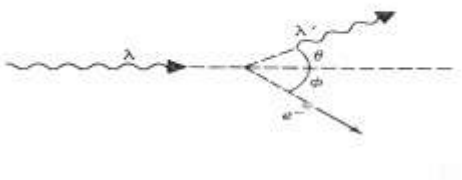



Fig 8

**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 the classic model cannot not explain the presence of the second band (λ') in scattered radiation spectra.**

- Compton could explain the ***results*** of his experiments by modelling *X-rays* as a set of ***photons*** that behave as particles that contain a ***linear momentum*.** He modelled incident X-radiation as a beam of "***X*-photons**" i.e. *quantum particules*. Also, he performed calculations in a **relativistic frame** for the collision of two "*single particles*" (one X-*photon and one "free" electron at external shell of carbon atom*) .

The energy of incident X-ray photon is much larger than ***binding energy of electrons in the external shells*** of C-atoms at 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

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

The conservation of ***linear momentum*** for the set (*photon - electron*) before/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 "θ" for deflected X-photon and "φ" for deflected $e^-$ (see Fig.8), the projection of vector relation (20) on axes gives

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

*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*

$$p^2 = (\frac{h}{\lambda} - \frac{h}{\lambda'}cos\theta)^2 + \frac{h^2}{\lambda'^2}sin^2\theta = \frac{h^2}{\lambda^2} - 2\frac{h}{\lambda}\frac{h}{\lambda'}cos\theta + \frac{h^2}{\lambda'^2}cos^2\theta + \frac{h^2}{\lambda'^2}sin^2\theta = \frac{h^2}{\lambda^2} + \frac{h^2}{\lambda'^2} - 2\frac{h}{\lambda}\frac{h}{\lambda'}cos\theta$$

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

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

$$p^2 = \frac{1}{c^2}(K^2 + 2KE_0) = \frac{1}{c^2}\left[\left(\frac{hc}{\lambda} - \frac{hc}{\lambda'}\right)^2 + 2\left(\frac{hc}{\lambda} - \frac{hc}{\lambda'}\right)m_0^{el}c^2\right] = \frac{1}{c^2}\left[c^2h^2\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right)^2 + 2c^2h^2\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right)\frac{m_0^{el}c}{h}\right]$$

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

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

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

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

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 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 λ'- 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 λ'- component in scattered radiation and provides an expression that fits to experimental recordings.

## 4.THE LINE SPECTRA

- As mentioned, 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*** and ***656.21*** nm. The first step in the study of hydrogen spectrum was 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 all four measured λ-values for shown m- values.

- Niels Bohr built a physical model that offered an explanation for the origin of line spectra from the atom of hydrogen. 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 is an unacceptable assumption for classical physics but it 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

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

-Figure 10 presents the energy level diagram for hydrogen (***Z=1***). Each ***state*** of ***electron - nucleus system*** (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 expression (26) and find out that:

$$E_1 = -13.6eV,\ E_2 = -13.6/2^2 = -3.4eV,\ E_3 = -13.6/3^2 = -1.51eV\ ...$$

The **energy zero** corresponds to the "***largest orbit***" (n = ∞ 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* tents to be in the *lower level of energy* which corresponds to the *most stable configuration* of the system.
So, for a collection of many atoms, ***in normal conditions***, majority of electrons *populate the lowest levels of energy*.

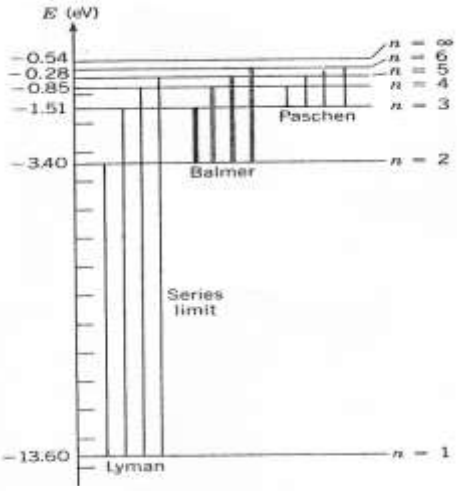



Fig.9

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

-A bound *electron can be raised to a higher energy level by* ***absorbing a photon*** *but this can happen* ***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 it has continuous energy if it is unbound.* So, an electron *c*an 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,..) to the level with* ***n = 2***. The emitted photons during those transitions produce four spectral lines in the ***visible*** spectrum of hydrogen.
The transitions started *from* levels with *n=2,3,4,..* ***to the level with n =1*** form the ***Lyman*** emission series ***(all lines in UV).***
The transitions started *from* levels with *n=4,5,6,..* ***to the level with n=3*** form the ***Paschen*** emission series ***(all lines in IR )***.

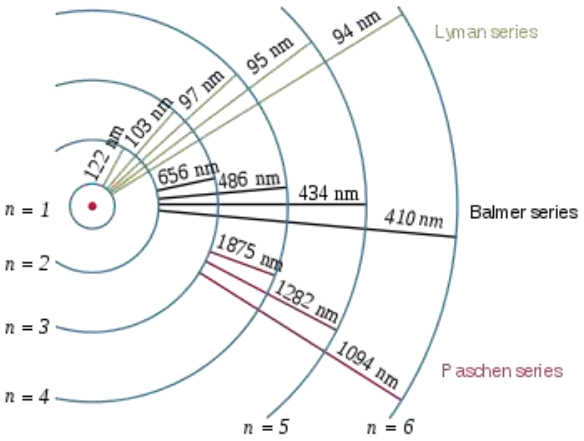



Fig.10

Transitions between the "allowed circular orbits" of H- atom in Bohr model.