

# Chapter One

## The Old Quantum Theory

### **1- 1 Why Quantum Mechanics.**

The birth of quantum mechanics can be dated to 1925, when physicists such as Werner Heisenberg and Erwin Schrödinger invented mathematical procedures that accurately replicated many of the observed properties of atoms. The change from earlier types of physics was dramatic, and pre-quantum physics was soon called classical physics in a kind of nostalgia for the days when waves were waves, particles were particles, and everything knew its place in the world.

Since 1925, quantum mechanics has never looked back. It soon became clear that the new methods were not just good at accounting for the properties of atoms, they were absolutely central to explaining why atoms did not collapse, how solids can be rigid, and how different atoms combine together in what we call chemistry and biology. The rules of classical physics, far from being a reliable description of the everyday world that breaks down at the scale of the atom, turned out to be incapable of explaining anything much more complicated than how planets orbit the sun, unless they used either the results of quantum mechanics or a lot of ad hoc assumptions.

But this triumph of quantum mechanics came with an unexpected problem-when you stepped outside of the mathematics and tried to explain what was going on, it didn't seem to make any sense. Elementary particles such as electrons behave like waves, apparently moving like ripples on a pond; they also seem to be instantaneously aware of distant objects and to be in different places at the same time. It seemed that any weird idea could gain respectability by finding similarities with some of the weird features of quantum mechanics. It has become almost obligatory to declare that quantum physics, in contrast to classical physics, cannot be understood, and that we should admire its ability to give the right answers without thinking about it too hard.

And yet, eighty years and unprecedented numbers of physicists later, naked quantum weirdness remains elusive. There are plenty of quantum phenomena, from the magnetism of iron and the superconductivity of lead to lasers and electronics, but none of them really qualifies as truly bizarre in the way we might expect. The greatest mystery of quantum mechanics is how its ideas have remained so weird while it explained more and more about the world around us.

## **1-2 Black- Body Radiation:**

### **1-2-1 Definition of black- body radiation**

A black body is an ideal body which allows the whole of the incident radiation to pass into itself ( without reflecting the energy) and absorbs within itself this whole incident radiation ( without passing on the energy). This property is valid for radiation corresponding to all wavelengths and to all angles of incidence. Therefore, the black body is an ideal absorber of incident radiation. All other qualitative characteristics determining the behavior of a black body follow from this definition ( see, for example, Siegel and Howell, 1972; Ozisik, 1973)

*Objects* at around room temperature emit mainly infra-red radiation ( $\lambda \gg 10\text{mm}$ ) which is invisible. *The sun* emits most of its radiation at visible wavelengths, particularly yellow ( $\lambda \approx 0.5\text{mm}$ ). A simple example of a black body radiator is the furnace. If there is a small hole in the door of the furnace heat energy can enter from the outside. Inside the furnace this is absorbed by the inside walls. The walls are very hot and are also emitting thermal radiation. This may be absorbed by another part of the furnace wall or it may escape through the hole in the door. This radiation that escapes may contain any wavelength. The furnace is in equilibrium as when it absorbs some radiation it emits some to make up for this and eventually a small amount of this emitted radiation may escape to compensate for the radiation that entered through the hole. *Stars* are also approximate black body radiators. Most of the light directed at a star is absorbed. It is therefore capable of absorbing all wavelengths of electromagnetic radiation, so is also capable of emitting all wavelengths of electromagnetic radiation. Most approximate blackbodies are

solids but stars are an exception because the gas particles in them are so dense they are capable of absorbing the majority of the radiant energy.

### 1-2-2 Black body radiation curves

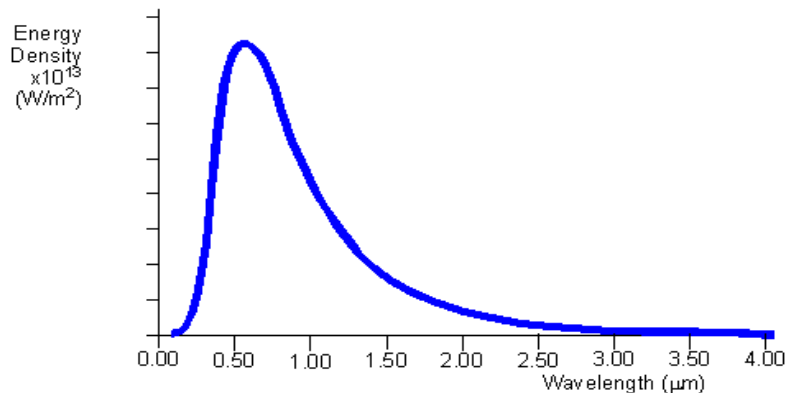


Fig 1: Theoretical black body curve for 5000K

The black body radiation curve (Figure 1-1) shows that the black body does radiate energy at every wavelength. The curve gets infinitely close to the x-axis but never touches it. The curve touches at infinite wavelength. It also shows that the black body emits at a peak wavelength, at which most of the radiant energy is emitted. At 5000K the peak wavelength is about  $5 \times 10^{-7} \text{m}$  (500nm) which is in the visible light region, in the yellow-green section. At each temperature the black body emits a standard amount of energy. This is represented by the area under the curve.

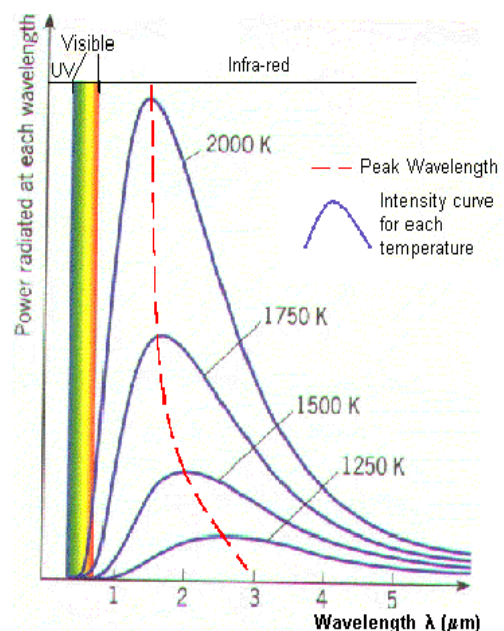


Fig. 1-2: Black body radiation curves showing peak wavelengths at various

The curves in figure (1-2), shows how the black body radiation curves change at various temperatures. These all have their peak wavelengths in the infra-red part of the spectrum as they are at a lower temperature than the previous graph. The graph shows: As the temperature increases, the peak wavelength emitted by the black body decreases. It therefore begins to move from the infra-red towards the visible part of the spectrum. Again, none of the graphs touch the x-axis so they emit at every wavelength. This means that some visible radiation is emitted even at these lower temperatures and at any temperature above absolute zero, a black body will emit some visible light. The graph also shows: As temperature increases, the total energy emitted increases, because the total area under the curve increases. It also shows that the relationship is not linear as the area does not increase in even steps. The rate of increase of area and therefore energy increases as temperature increases.

### **1-2-3 Wien's law**

The wiwn' law is written as:

$$\lambda_p = \textit{constant} \quad (1-1)$$

Where  $\lambda_p = 2.898 \times 10^{-3} / T$

$\lambda_p$ =Peak Wavelength (m) , T=Surface Temperature (K), and Constant= $2.898 \times 10^{-3} \text{ mK}$

This rearranged equation shows why the peak wavelength decreases as temperature increases. This decrease in wavelength explains why objects glow first red, then orange-red, then yellow, then even blue. These colours are successive decreases in wavelength.

#### **1-2-4 STEFAN'S LAW**

This law is written as:

$$P = \sigma AT^4 \quad (1-2)$$

Where P= Power radiated in W (J/s)

$\sigma$  = Stefan's Constant  $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

A = Surface area of body ( $\text{m}^2$ )

T = Temperature of body (K)

Therefore the Power radiated is proportional to  $T^4$  for an identical body which explains why the area under the black body curves (the total energy) increases so much for a relatively small increase in temperature.

#### **1-2-5 Planck energy distribution formula**

$$E_\lambda = \frac{2\pi hc^2}{\lambda^5 \left( e^{\frac{hc}{\lambda kT}} - 1 \right)} \quad (1-3)$$

Where:

P=Power per  $\text{m}^2$  area per m wavelength, h = Planck's constant ( $6.626 \times 10^{-34} \text{ Js}$ ), c = Speed of Light ( $3 \times 10^8 \text{ m/s}$ ),  $\lambda$  = Wavelength (m), k = Boltzmann Constant ( $1.38 \times 10^{-23} \text{ J/K}$ ) , and T = Temperature (K).

This complex looking formula is used to plot the black body curves for each temperature by working out the power emitted at each wavelength.

#### **1-2-6 Ultraviolet catastrophe**

In the 19th century a major problem for physicists was to predict the intensity of radiation emitted by a black body at a specific wavelength. Wilhelm Wien made a theory that predicted the overall form of the curve by treating the radiation as gas molecules. However, at long wavelengths his theory disagreed with experimental data. Rayleigh and Jeans then produced a formula by considering the radiation within the black body cavity to be

made up of a series of standing waves. They thought that electromagnetic radiation was emitted by oscillating atoms in the walls of the black body and this radiation set up a standing wave between the walls. Their formula stated:

$$I = \frac{2\pi c k T}{\lambda^4}$$

I = Intensity

However, this formula also had a problem. For large wavelengths it fitted the experimental data but it had major problems at shorter wavelengths. The problem was the  $\lambda$  term in the denominator. It meant that as the wavelength tended to zero, the curve would tend to infinity. However we know that there is a peak wavelength for each temperature, and the energy emitted at either side of this peak dropped. The Rayleigh-Jeans Law predicted no peak wavelength.

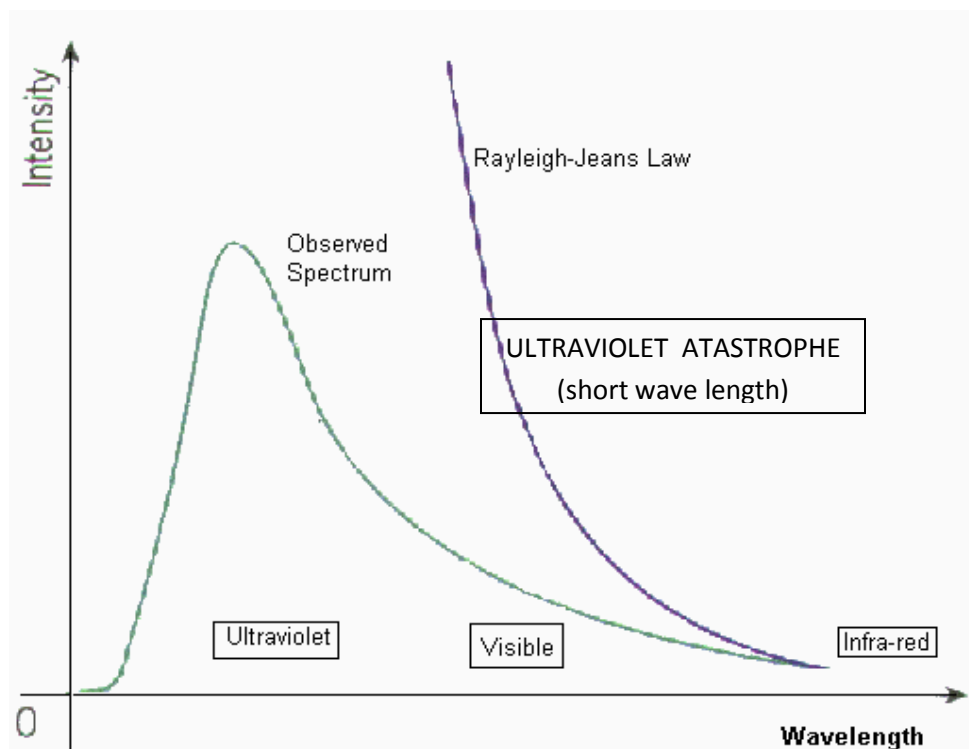


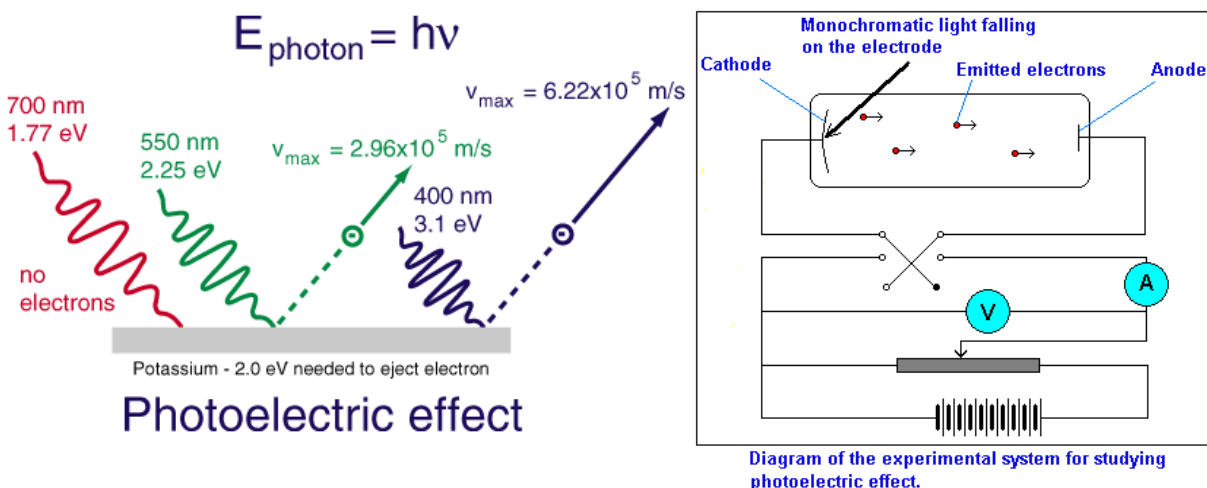
Fig. 1-3 : Comparison of Experimental black body data and Rayleigh-Jeans Law

Therefore the wave theory of the time could be used to explain behavior on either side of the peak (Figure 1-3), but the peak would be infinitely high. The failure of these formulae to account for the decrease in energy emitted at short wavelengths (*the ultraviolet wavelengths*) became known as the ultraviolet catastrophe. A major breakthrough was made by **Max Planck** who made a formula that agreed with experimental data, which is showed in equation(1-3). However, he had major problems proving this law. His idea was that the oscillating electrons of the surface atoms of the black body emitted radiation according to *Maxwell's laws of electromagnetism*. Before Planck it was assumed that these could have any value of energy but Planck decided that the energy must go up in discrete amounts (*quantized*) because the frequencies of the oscillating electrons could only take certain values. As energy is proportional to frequency ( $E=hf$ ), where  $h$  is the Planck constant ( $6.626 \times 10^{-34}$  Js) if frequency can only take discrete values, this means that energy is also quantized. The electrons have a fundamental frequency (like standing waves on a string) and the frequency can only go up in whole multiples of this frequency, called the quantum number. This assumption led Planck to correctly derive his formula. If he ignored the quantized energy, he obtained the Rayleigh-Jeans formula. Einstein took the next step by working out that all radiation is quantized. He argued that an oscillating charge can accept or lose energy in small values of  $\Delta E = h\Delta f$ . This energy is lost as electromagnetic radiation. Therefore this radiation must be emitted in small packets, each containing  $\Delta E$ . He then suggested that each energy of radiation will have its own frequency. Therefore he no longer thought of radiation from an object as continuous. He said it consisted of a series of "packets" of energy. This meant that radiation was being thought of as a

"packet of energy" but also as a wave because it had a frequency. These became known as photons.

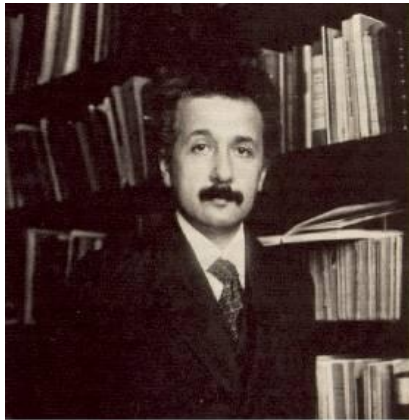
### 1-3 The Photo Electric Effect

As successful as the *Plank Formula* was, the conclusion from it of the quantum nature of radiation is hardly compelling. An important contribution to its acceptance came from the work of *Albert Einstein*, who in 1905 used concept of the quantum nature of light to explain some peculiar properties of metal, when these are irradiated with visible and ultraviolet light.



In 1887, the photoelectric effect was discovered by *Hertz*, who, while engaged in his famous experiments on electromagnetic waves, found that the length of the spark induced in the secondary circuit was reduced when the terminals of the spark gap were shielded from the ultraviolet light coming from the spark in the primary circuit.





Albert Einstein

*(won Einstein his Nobel Prize in 1921)*



Rudolf Hertz

### **1-3-1 Equations**

Einstein's formula relates the maximum kinetic energy ( $K_{max}$ ) of the photoelectrons to the frequency of the absorbed photons ( $f$ ) and the threshold frequency ( $f_0$ ) of the photo emissive surface. (This formula is only approximate, however, and a minor correction is needed for the Compton Effect.)

$$K_{max} = h(f - f_0) \quad (1-5)$$

or if you prefer, to the energy of the absorbed photons ( $E$ ) and the **work function** ( $\phi$ ) of the surface

$$K_{max} = E - \phi \quad (1-6)$$

where the first term is the energy of the absorbed photons ( $E$ ) with frequency ( $f$ ) or wavelength ( $\lambda$ )

$$E = hf = \frac{hc}{\lambda} \quad (1-7)$$

and the second term is the work function ( $\phi$ ) of the surface with threshold frequency ( $f_0$ ) or threshold wavelength ( $\lambda_0$ )

$$\phi = hf_0 = \frac{hc}{\lambda_0}$$

The maximum kinetic energy ( $K_{max}$ ) of the photoelectrons (with charge  $e$ ) can be determined from the stopping potential ( $V_0$ ).

$$V_0 = \frac{W}{q} = \frac{K_{max}}{e} \text{ thus } K_{max} = eV_0 \quad (1-8)$$

When charge ( $e$ ) is given in coulombs, the energy will be calculated in joules. When charge is given in elementary charges, the energy will be calculated in electron volts.

The rate ( $n/t$ ) at which photoelectrons (with charge  $e$ ) are emitted from a photoemissive surface can be determined from the photoelectric current ( $I$ ).

$$I = \frac{q}{t} = \frac{ne}{t} \text{ thus } \frac{n}{t} = \frac{I}{e} \quad (1-9)$$

Planck's Constant

- $h = 6.63 \times 10^{-34} \text{ J s} = 4.14 \times 10^{-15} \text{ eV s}$
- $hc = 1.99 \times 10^{-25} \text{ J m} = 1240 \text{ eV nm}$

## 1-4 Compton Scattering

Arthur H. Compton observed the scattering of *x-rays* from electrons in a carbon target and found scattered x-rays with a longer wavelength than those incident upon the target. The shift of the wavelength increased with scattering angle according to the Compton formula:

$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_e c} (1 - \cos \theta) \quad (1-8)$$

Compton explained and modeled the data by assuming a particle (photon) nature for light and applying conservation of energy and conservation of momentum to the collision between the photon and the electron Figure (1- ). The scattered photon has lower energy and therefore a longer wavelength according to the Planck relationship.

At a time (early 1920's) when the particle (photon) nature of light suggested by the [photoelectric effect](#) was still being debated, the Compton experiment gave clear and independent evidence of particle-like behavior. Compton was awarded the Nobel Prize in 1927 for the "discovery of the effect named after him".

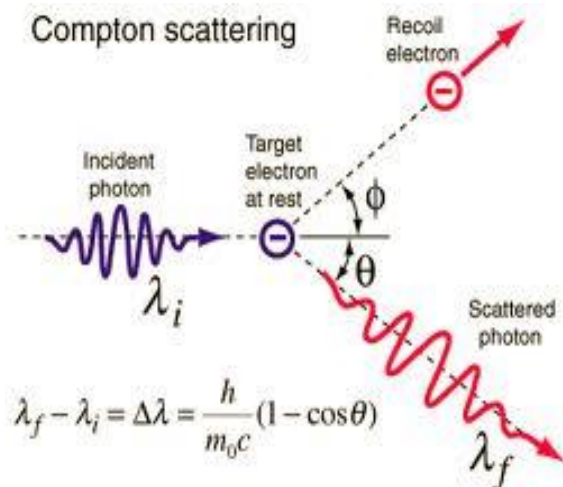
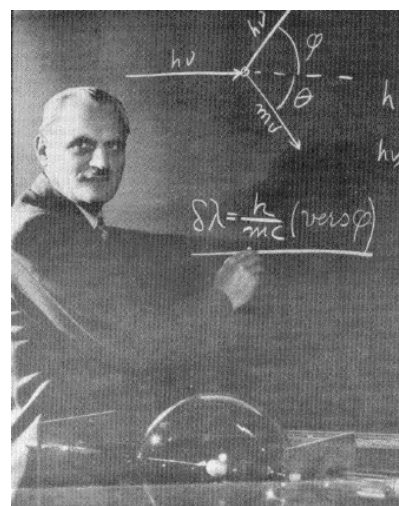


Figure ( 1- ). Digram Show Compton Scattering



Arthur Holly Compton and the Compton scattering formula