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Paper: C9T (Elements of Modern Physics)

Topic: Development of Modern Physics (Unit 1)

Before we try to understand modern physics, we should be familiar with the main events in the evolution of natural science over the centuries. At least we must talk about the events i.e. experiments and/or theoretical developments which have given birth to the modern theories in physics which quantitatively described the phenomena which could not be explained by the classical theories of physics. Modern physics is basically a collection of these present day theories. Theory of relativity and quantum theory are the two great conceptual remodelings of classical physics and form the basis of modern physics.

We will mainly talk about the development of quantum theory through the ground breaking works of Planck, Einstein, de Broglie, Schrodinger and many. The concept of quantum theory was first proposed by Planck in 1900 to explain the spectrum of a blackbody which was not fully explained by classical physics. Planck assumed the electromagnetic (EM) radiation was emitted by harmonic oscillators and the energy of EM radiation can change only by discrete jumps of amount $h\nu$. Planck was successful in explaining blackbody radiation with these groundbreaking assumptions.

Now, we will discuss blackbody radiation, its initial classical descriptions, failure of classical theories and finally the Planck's quantum concept which successfully explains the blackbody radiation.

Blackbody Radiation

A blackbody is an idealized physical object that absorbs all incident electromagnetic radiations irrespective of frequency or angle of incidence. Such a perfect absorber is also a perfect emitter of electromagnetic radiation. But, a blackbody does not reflect any radiation at all. The name "blackbody" is given because it absorbs electromagnetic radiations of ALL frequencies.

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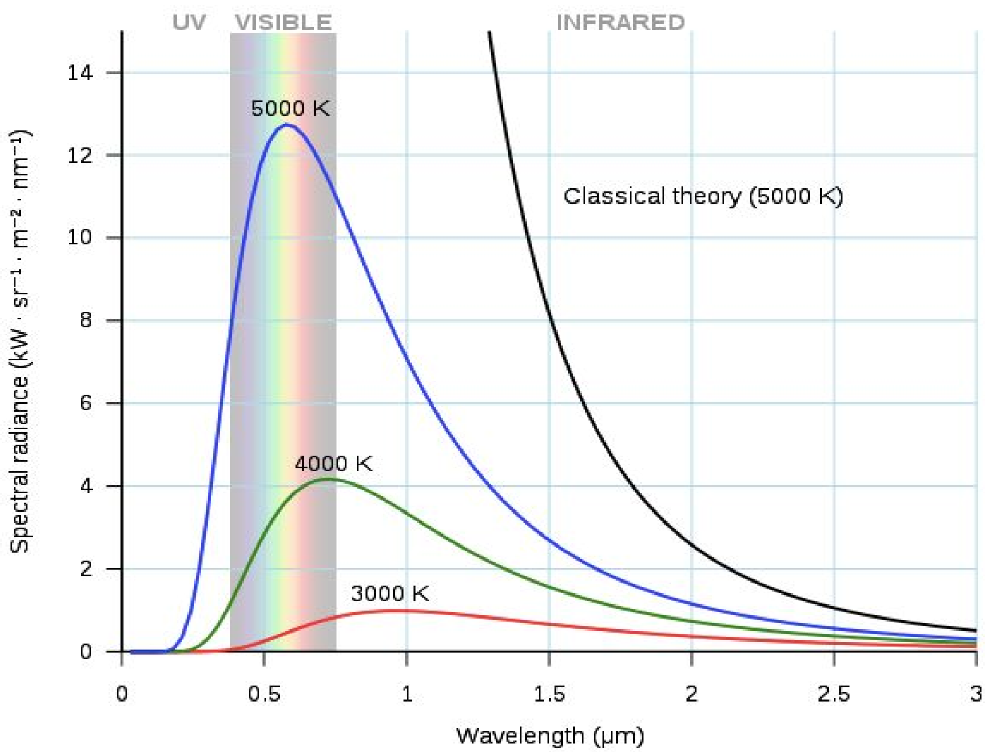
Blackbody radiation is the thermal radiation emitted by a blackbody in thermodynamic equilibrium with its environment. It has a spectrum of wavelengths, inversely related to intensity that depends only on the temperature of the blackbody. The spectral distribution of the thermal energy radiated by a blackbody is shown in the figure below.

The thermal radiations which are spontaneously emitted by many ordinary objects can be approximated as blackbody radiations. A perfectly insulated enclosure which is in thermal equilibrium internally (i.e. at a constant temperature) contains blackbody radiation and it can emit the radiation through a hole made in its wall, provided the hole is small enough so that it does not affect the equilibrium of the enclosure. So, such an enclosure can be called a blackbody.



As the temperature increases, the peak of the blackbody radiation curve moves to higher intensities and smaller wavelengths.

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We have learnt how total energy of the blackbody radiation is related to the temperature of the source through Stefan-Boltzmann law. The emitted radiation is spread over a continuous spectrum. But, how is the total energy of the radiation distributed amongst the different wavelengths? The attempts to find the answer to this question have a long story of development of physics including the revolutionary concept of quanta by Planck and eventually the quantum theory.

The answer to the above question is easy to find considering the quantum theory. It essentially becomes the problem of finding out how many quanta having energy between ϵ and ϵ+dϵ or frequency between ν and ν+dν are contained per unit volume in an enclosure of blackbody radiation at temperature T. But, it is the present day concept and it came after a long struggle.

Before the quantum theory was developed, the researchers of this field like Wien, Rayleigh, Jeans, Planck et. al were not aware of the mechanism of emission and absorption of radiation. In fact, this mechanism came to be known only through the work of Planck on blackbody radiation. They had to start with the existing knowledge on the laws of classical thermodynamics and electromagnetism. We will now chronologically discuss how these scientists found the solution to the problem of energy distribution in blackbody radiation.

The first development came from Wien in1893. From the thermodynamic consideration Wien found the energy distribution over the different wavelengths of emitted radiation from a blackbody at a temperature T to be as following

$$u_\lambda d\lambda = C\lambda^{-5}f(\lambda T)d\lambda$$

where $u_\lambda d_\lambda$ is the energy density of radiation between wavelengths λ and λ+dλ, C is a constant and f(λT) is a function of the product λT. This spectral distribution is known as **Wien's distribution law.**

As Wien's law fails to account for the experimental results at longer wavelengths, Rayleigh and Jeans came up with another approximation to the spectral radiance of electromagnetic radiation from a blackbody on the basis of two classical ideas of - (i) stationary waves in a hollow enclosure and (ii) law of equipartition of energy.

Blackbody radiation in an enclosure is composed of electromagnetic waves of wavelengths between 0 and ∞. These waves are reflected back and forth from the walls of the enclosure and form stationary waves in space. Rayleigh showed that the possible number of independent vibrations between the wavelengths **λ** and **λ**+d**λ** per unit volume is proportional to (1/**λ^4**)d**λ**. Also, according to the law of equipartition of energy, the energy corresponding to each vibrational mode will be K_BT (kinetic energy ½ K_BT and potential energy ½ K_BT). Using these classical concepts, Rayleigh and Jeans derived the distribution of energy for blackbody radiation in an enclosure at temperature T as

$$u_\lambda d\lambda = \frac{8\Pi K_B T}{\lambda^4} d\lambda$$

This is the ***Rayleigh-Jeans' law*** of spectral distribution of energy of Blackbody radiation.

Ultraviolet catastrophe is basically the failure of the classical theory of Rayleigh and Jeans to predict the spectral distribution of blackbody radiation. Though Rayleigh-Jeans' law matches the experimental results at higher wavelengths quite well, it fails miserably at lower wavelengths (or higher frequencies) i.e. at the ultraviolet range. According to Rayleigh-Jeans law, a blackbody at thermal equilibrium will emit radiation in all wavelength ranges, emitting extraordinarily more energy at lower wavelengths. The radiation energy diverges as $1/\lambda^4$ as the wavelength decreases. This suggests that all matter would radiate all its energy instantaneously contradicting the experimental facts. This is known as ***ultraviolet catastrophe*** or ***Rayleigh-Jeans' catastrophe***.

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Planck's Quantum Concept

The laws of radiation as deduced theoretically using classical concepts by Wien and Rayleigh-Jeans failed to explain experimentally observed energy distribution amongst the different wavelengths. The drawbacks and failures of classical theories in explaining blackbody radiation were overcome by Max Planck in 1900 through his groundbreaking assumption. ***Planck assumed the electromagnetic (EM) radiation was emitted by harmonic oscillators and the energy of EM radiation can change only by discrete energy jumps of amount hν. On the basis of this assumption, Planck deduced the most satisfactory formula both on the theoretical and experimental grounds.*** He derived the energy distribution formula for blackbody radiation as following:

$$u_\lambda d\lambda = \frac{8hc}{\lambda^5}\frac{1}{exp(\frac{hc}{\lambda K_B T}-1)}d\lambda$$

This formula agrees with the experimental results of blackbody radiations and resolved the problems of classical formulas.

Photoelectric effect

Photoelectric effect is another very important phenomenon which was first satisfactorily explained by Einstein in 1905 by extending Planck's concept of quantized energy of electromagnetic radiation. Einstein considered that the interchange of energy between the light (electromagnetic radiation) and matter take place in energy quanta of magnitude **hν.** Einstein assumed that a whole quantum ***hν*** of radiant energy was absorbed by a single electron. This implies that not only the radiant energy emitted in quanta of energy ***hν*** but also it is transmitted as a localized energy packet to be absorbed as a unit. Such a quantum of electromagnetic radiation is called a **photon**.

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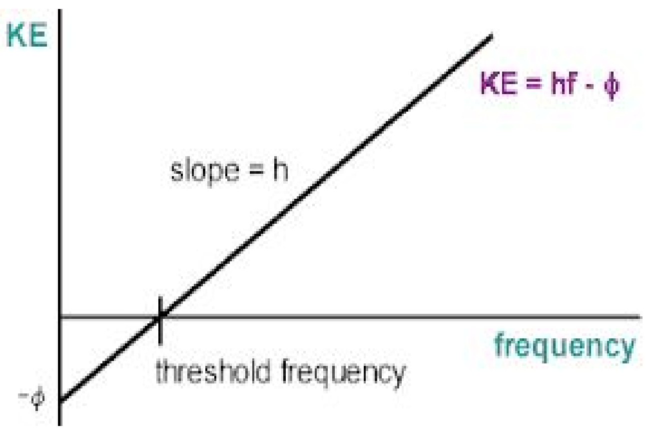
Einstein further proposed that if ϕ_0 be the minimum energy required to free an electron from a metal then the maximum kinetic energy K_{max} of the photoelectrons freed by photons of energy $h\nu$ is given by

$$K_{max} = h\nu - \phi_0$$

This equation is known as Einstein's photoelectric equation. At the time of this development, only qualitative data were available and this equation gave results of the correct order of magnitude. Later on, it was verified by different experiments.



The variation of maximum kinetic energy of photoelectrons with the frequency of the incident radiation is plotted in the above figure. Below the threshold frequency *($\nu_0 = \phi_0/h$),* there will be no emission of electrons.

This equation is in fact valid for x-rays, the frequencies of which are several thousand times the frequencies of visible light. Einstein's photoelectric equation played an extremely important role in the development of modern quantum theory. Einstein was awarded the Nobel Prize in Physics 1921 for "his discovery of the law of the photoelectric effect".

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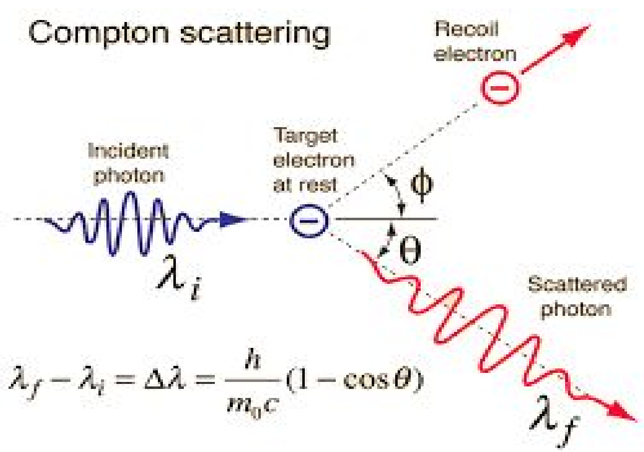
Compton Scattering

Compton scattering, discovered by the scientist A H Compton, is basically scattering of a photon by a charged particle, usually an electron inside a material. In the process of the scattering, the photon (generally x-ray or gamma ray photon) loses its energy that means the wavelength of the scattered photon increases. This is known as Compton effect. The part of the energy of the photon is transferred to the recoiling electron.

The change or shift in the wavelength of the photon increases with the scattering angle according to the Compton's formula:

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

Compton derived this formula and explained the effect using the particle (photon) nature of radiation and applying conservation of energy and conservation of momentum to the collision of the photon and the electron. The scattered photon has lower energy and therefore a longer wavelength according to the Planck's relationship $E = h\nu = hc/\lambda$.



Compton observed and explained this phenomenon in the early 1923, at a time when the particle nature of light was still being debated. This experiment gave a clear and independent evidence of the particle-like behavior of light. Compton was awarded the Nobel Prize in 1927 for the discovery of the effect, which is named after him, Compton's effect.

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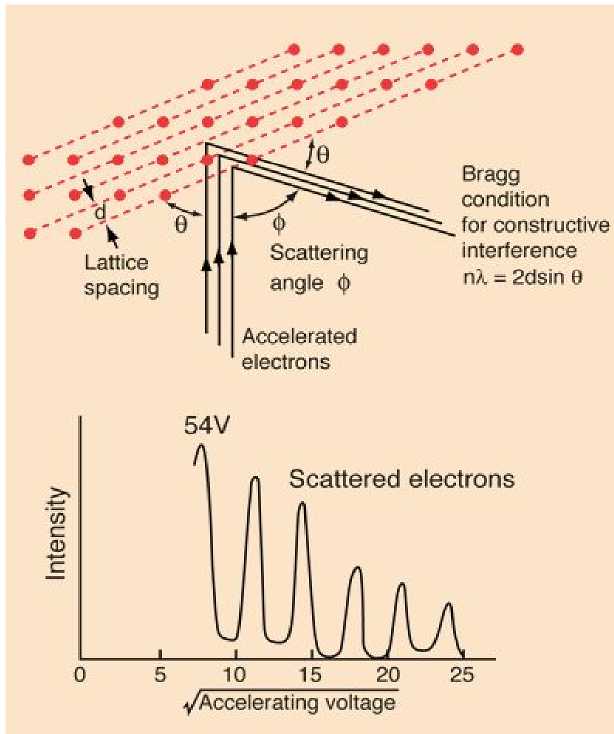
Davisson-Germer experiment

The Davisson-Germer experiment was a long experiment (1923-1927) by Clinton Davisson and Lester Germer, in which electrons scattered by the surface of a nickel crystal displayed a diffraction pattern. This demonstrated the wave nature of electrons confirming the hypothesis of de Broglie (1924). So, this experiment confirmed the wave-particle duality and it became an important milestone in the development of quantum mechanics.

Davisson and Germer had designed and built a vacuum system for measuring the energies of electrons scattered from a metal surface. The electrons from a heated hot filament were accelerated by a voltage and were allowed to strike the nickel surface. There was a mechanism to rotate the electron beam to observe the angular dependence of the scattered electrons. Also their electron detector (Faraday box) was mounted on a rotating arc to observe electrons at different angles.



To their great surprise, they observed high intensity of the scattered electron beam at certain angles and low intensity at certain other angles. This indicated the wave nature of the electrons. Davisson and Germer used Bragg's law to interpret their data and calculated the lattice spacing of the nickel crystal. Bragg's law of diffraction had been used to interpret x-ray diffraction but this was the first time when Davisson and Germer applied Bragg's law to the matter waves.

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Wave-Particle Duality

Wave-particle duality is the concept of quantum mechanics which says that every particle or quantum entity can be described either as particle or as wave. As Einstein wrote:

"*It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do."*

We now know through the works of Planck, Einstein, de Broglie, Compton, Bohr and many others, that all particles exhibit wave nature and all waves have particle nature. This phenomenon has been observed not only for elementary particles but also for compound particles like atoms and even molecules. We can't observe the wave nature of the macroscopic particles because of their extremely short wavelengths.

Matter Waves:

Matter waves are an important part of quantum mechanics. It is also an example of wave-particle duality. All matter exhibits wave-like behaviors. As an example, a beam of electrons can be diffracted like a beam of light. This concept was first proposed by Louis de Broglie in 1924. It is also known as de Broglie hypothesis and the matter waves are also called de Broglie waves.

de Broglie hypothesis:

All matter has wave-like nature and the wavelength λ associated with a particle with momentum p is given by

$$\lambda = \frac{h}{p} = mv$$

The wave nature of matter was first experimentally demonstrated by Thomson's metal diffraction experiment and independently in the Davisson-Germer experiment.

References:

(i) Introduction to Modern Physics - Richtmyer, Kennard, Cooper
(ii)https://en.wikipedia.org/wiki/Black-body_radiation#/media/File:Black_body.svg
(ii) http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html
(iii) http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/DavGer2.html

N.B.: Some of the figures used in this study material are taken from the above websites for teaching purposes only.