Dual Nature of Matter and Radiation

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Einstein in 1905, suggested that light has dual nature i.e., wave nature as well as particle nature. Louis de Broglie, a French physicist, in 1924, advanced the idea that like photons, all material particle such as electron, proton, atom, molecules, a piece of chalk, a piece of stone or an iron ball (microscopic as well as macroscopic objects) also possessed dual character. The wave associated with a particle is called a matter wave or de Broglie wave.

The de Broglie relation: The wavelength of the wave associated with any material particle was calculated by analogy with photon as: In case of a photon, if it is assumed to have wave character, its energy is given by

$E = h\nu$ (i) (according to the **Planck's quantum theory**)

If the photon is supposed to have particle character, its energy is given by

$E = mc^2$ (ii) (according to **Einstein**)

Where m is the mass of photon and c is the velocity of light. From equations (i) and (ii), we get,

$h\nu = mc^2$ but $\nu = c/\lambda$ $\therefore$ $h. c/\lambda = mc^2$ or $\lambda = h/mc$

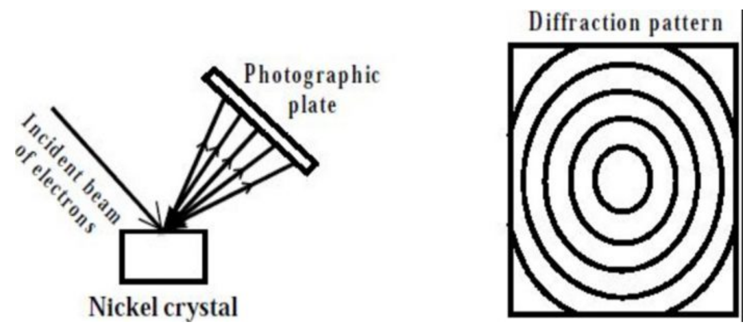
de Broglie pointed out that the above equation is applicable to any material particle. The mass of the photon is replace by the mass of the material particle and velocity 'c' of the photon is replaced by the velocity 'v' of the material particle. Thus, for any material particle like electron, we may write $\lambda = h/mv$ or $\lambda = h/p$ where $mv = p$ is the momentum of the particle.

The above equation is called de Broglie equation and λ is called de Broglie wavelength. This equation shows that $\lambda \propto 1/p$. i.e., de Broglie wave length of a particle is inversely proportional to its momentum. Thus, the significance of de Broglie equation lies in the fact that it relates the particle character with the wave character of matter.

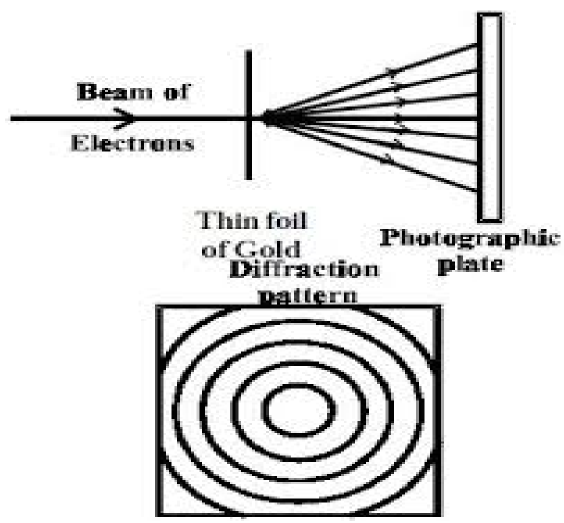
Significance of de Broglie equation: Although de Broglie equation is applicable to all material objects but it has significance only in case of microscopic particles. For example- consider a ball of mass 0.1kg moving with a speed of 60m/s. From de Broglie equation, the wavelength of associated wave is h/mv = $6.62\text{x}10^{-34}\text{kgm}^2\text{s}^{-1}$ /0.1kg x $60\text{ms}^{-1} \approx 10^{-34}$ m. It is apparent that this wavelength is too small for ordinary observation. On the other hand, an electron with rest mass equal to $9.11\text{x}10^{-31}\text{kg} \approx 10^{-30}\text{kg}$ moving at the same speed would have a wavelength = $6.62\text{x}10^{-34}\text{kgm}^2\text{s}^{-1}$ /10^{-30} kg x $60\text{ms}^{-1} \approx 10^{-5}$ m = 10^5Å which can be easily measured experimentally. Since we come across macroscopic objects in our everyday life, therefore de Broglie relationship has no significance in everyday life. That is why we do not observe any wave nature associated with the motion of a running car or a cricket ball etc.

Experimental verification of dual character of electrons:

(a) verification of wave character: Davisson and Germer's experiment (1927): In this experiment it was observed that when a beam of electron is allowed to fall on the surface of a nickel crystal and the scattered or the reflected rays are received on a photographic plate, a diffraction pattern (consisting of a number of concentric rings), similar to that produced by X-rays, is obtained. Now, since X-rays are electromagnetic waves, i.e., they are confirmed to have character, therefore, electrons must have wave character. Moreover, the wavelength determined from the diffraction pattern is found to be very nearly the same as calculated from de Broglie equation. This further lent support to de Broglie equation.



Thomson's experiment: G.P.Thomson in 1928, performed experiments with thin foil of gold in place of nickel crystal. He observed that if the beam of electrons after passing through the thin foil of gold is received on the photographic plate placed perpendicular to the direction of the beam, a diffraction pattern is observed. This again confirmed the wave nature of electrons.



Verification of the particle character: When an electron strikes a zinc sulphide screen a spot of light known as scintillation is produced. Since scintillation is localized on the zinc sulphide screen, therefore the striking electron which produced it also must be localized and is not spread out on the screen. But the localized character is possessed by particles. Hence, electron has particle character.

Calculation of de-Broglie wavelength of the electron: If accelerating potential V is applied to an electron beam, the energy acquired by the electron is expressed in electron-volt (eV) which is equal to charge on the electron in coulombs X potential applied in volts. This energy becomes the kinetic energy of the electron.

As kinetic energy = ½ mv^2, hence, ½ $mv^2 = eV$ or $v = \sqrt{2eV/m}$

$$\therefore \lambda = h/mv = h/m \times \sqrt{2eV/m} = h/\sqrt{2meV}$$

Substituting the values of various constants,

$h = 6.626 \times 10^{-34} kgm^2s^{-1}$

$m = 9.11 \times 10^{-31} kg$

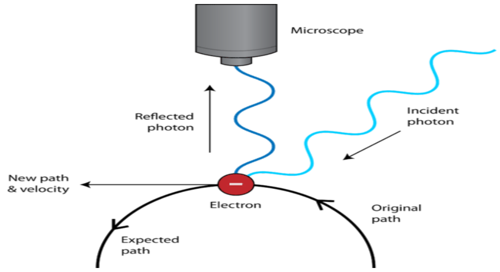
$e = 1.602 \times 10^{-19} c$, we get $\lambda = 1.226 \times 10^{-9}/\sqrt{V}$ meter

Derivation of Bohr's postulate of angular momentum from de-Broglie equation: According to Bohr's model, the electron revolves around the nucleus in circular orbits. According to de-Broglie concept, the electron is not only a particle but has a wave character. Thus, in order that the wave may be completely in phase, the circumference of the orbit must be equal to an integral multiple of wavelength (λ). Therefore, $2\pi r = n\lambda$ where r is the radius of the orbit and n is an integer. But $\lambda = h/mv$ (de-Broglie eq.), $2\pi r = n\lambda = nh/mv$ or $mvr = nh/2\pi$ which is Bohr's postulate of angular momentum.

Heisenberg's uncertainty principle: ''It is impossible to measure simultaneously the position and momentum of a small particle with absolute accuracy or certainty.'' If an attempt is made to measure any one of these two quantities with higher accuracy, the other becomes less accurate. The product of the uncertainty in the position (Δx) and the uncertainty in the momentum (Δp) is always constant and is equal to or greater than $h/4\pi$, where h is Planck's constant.

So $\Delta x . \Delta p \geq h/4\pi$. The mathematical expression for Heisenberg's uncertainty principle is simply written as: $\Delta x . \Delta p \approx h/4\pi$ ($\Delta p = m . \Delta v$ where m is the mass of the particle and Δv is the uncertainty in velocity). Putting $\Delta p = m . \Delta v$ in the eq. of uncertainity, we get $\Delta x . m\Delta v \geq h/4\pi$ or $\Delta x . \Delta v \geq h/4\pi m$. This implies that the position and velocity of a particle cannot be measured simultaneously with certainty.

Explanation: Let us consider an electron moving along a certain path. In order to observe the electron, some photon of light must fall on it so that the reflected photon can be observed in the microscope.



But the accuracy with which we can observe the particle depends upon the wavelength of light used. Shorter the wavelength greater will be the accuracy. But shorter wavelength means higher frequency and therefore higher energy ($E=h\nu$). Therefore, when this high energy photon strikes on electron, it changes its velocity as well as direction.

Significance of Heisenberg's uncertainty: This principle holds good for all objects but it is of significance only for microscopic particles. The energy of the photon is insufficient to change the position and velocity of bigger bodies when it collides with them. For example, the light from a torch falling on a running rat in a dark room neither changes the speed of the rat nor its direction. Since in everyday life, we come across big objects only, the position and velocity of which can be measured accurately. Heisenberg's uncertainty principle has no significance in everyday life.

Why electron cannot exist in the nucleus: Heisenberg's uncertainty principle explains that why electrons cannot exist within the nucleus, because the diameter of the atomic nucleus is of the order of 10^{-14}m. Hence if the electron were to exist within the nucleus, the maximum uncertainty in its position would have been 10^{-14}m. As such for the electron to exist within the nucleus, its uncertainty in position must also be of the order of 10^{-14}m. Taking mass of electron 9.1 x 10^{-31}kg, the uncertainity in velocity will be :

$$\Delta x. \Delta p \approx h/4\pi$$

$$\Delta x. m\Delta v \geq h/4\pi$$

$$\Delta v = h/4\pi\ \Delta x. m$$

$$= 7x6.626x10^{-34}kgm^2s^{-1}/4x22x\ 9.1\ x\ 10^{-31}kg\ x\ 10^{-14}m.$$
$$= 6x10^9 m/s$$

This value is much higher than the velocity of light and hence it is not possible.

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