Chapter 20

ATOMIC SPECTRA

Learning Objectives

At the end of this chapter the students will be able to:

1. Know experimental facts of hydrogen spectrum.
2. Describe Bohr's postulates of hydrogen atom.
3. Explain hydrogen atom in terms of energy levels.
4. Describe de-Brogile's interpretation of Bohr's orbits.
5. Understand excitation and ionization potentials.
6. Describe uncertainty regarding position of electron in the atom.
7. Understand the production, properties and uses of X-rays.
8. Describe the terms spontaneous emission, stimulated emission, metastable states and population inversion.
9. Understand laser principle.
10. Describe the He-Ne gas laser.
11. Describe the application of laser including holography.

The branch of physics that deals with the investigation of wavelengths and intensities of electromagnetic radiation emitted or absorbed by atoms is called spectroscopy. It includes the study of spectra produced by atoms. In general there are three types of spectra called (i) continuous spectra, (ii) band spectra, and (iii) discrete or line spectra.

Black body radiation spectrum, as described in chapter 19 is an example of continuous spectra; molecular spectra are the examples of band spectra while the atomic spectra, which we shall investigate in detail in this chapter, are examples of discrete or line spectra.

20.1 ATOMIC SPECTRA

When an atomic gas or vapour at much less than atmospheric pressure is suitably excited, usually by passing an electric current through it, the emitted radiation has a spectrum, which contains certain specific wavelengths only. An idealized arrangement for observing such atomic spectra is shown in Fig. 20.1. Actual spectrometer uses diffraction grating for better results.

The impression on the screen is in the form of lines if the slit in front of the source S is narrow rectangle. It is for this reason that the spectrum is referred to as line spectrum.

The fact that the spectrum of any element contains wavelengths that exhibit definite regularities was utilized in the second half of the 19th century in identifying different elements.

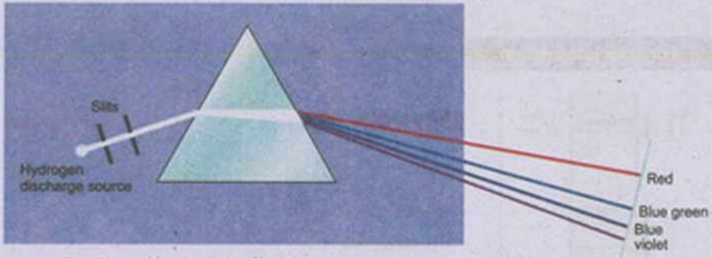


Fig. 20.1 Line spectrum of hydrogen

These regularities were classified into certain groups called the spectral series. The first such series was identified by J.J Balmer in 1885 in the spectrum of hydrogen. This series, called the Balmer series, is shown in Fig.20.2, and is in the visible region of the electromagnetic spectrum.

The results obtained by Balmer were expressed in 1896 by J.R Rydberg in the following mathematical form

$$\frac{1}{\lambda}=R_H\left(\frac{1}{2^2}-\frac{1}{n^2}\right) \quad \text{..........} \quad (20.1)$$

where R_H is the Rydberg's constant. Its value is $1.0974 \times 10^7\ m^{-1}$. Since then many more series have been discovered and proved helpful in predicting the arrangement of the electrons in different atoms.

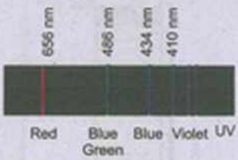


Fig. 20.2

Atomic Spectrum of Hydrogen

The Balmer series contain wavelengths in the visible portion of the hydrogen spectrum. The spectral lines of hydrogen in the ultraviolet and infrared regions fall into several other series. In the ultraviolet region, the Lyman series contains the wavelengths given by the formula

$$\frac{1}{\lambda}=R_H\left(\frac{1}{1^2}-\frac{1}{n^2}\right) \quad \text{..........} \quad (20.2)$$

where $n = 2, 3, 4, ...$

In the infrared region, three spectral series have been found whose lines have the wavelengths specified by the formulae:

For Your Information

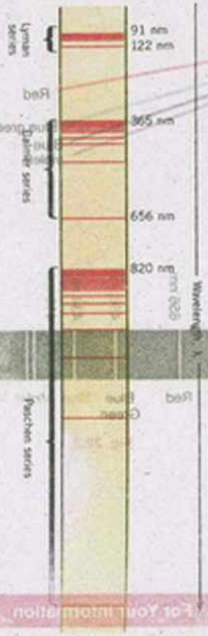
Different types of spectra

(a) Continuous spectrum

(b) Line spectrum

(c) Band spectrum

For Your Information



Line spectrum of atomic hydrogen. Only the Balmer series lies in the visible region of the electromagnetic spectrum.

Paschen series

$$\frac{1}{\lambda} = R_H\left(\frac{1}{3^2} - \frac{1}{n^2}\right) \quad \dots\dots\dots \quad (20.3)$$

where $n = 4, 5, 6, \dots\dots$

Brackett series

$$\frac{1}{\lambda} = R_H\left(\frac{1}{4^2} - \frac{1}{n^2}\right) \quad \dots\dots\dots \quad (20.4)$$

where $n = 5, 6, 7, \dots\dots$

Pfund series

$$\frac{1}{\lambda} = R_H\left(\frac{1}{5^2} - \frac{1}{n^2}\right) \quad \dots\dots\dots \quad (20.5)$$

where $n = 6, 7, 8,$

The existence of these regularities in the hydrogen spectrum together with similar regularities in the spectra of more complex elements, proposes a definite test for any theory of atomic structure.

20.2 BOHR'S MODEL OF THE HYDROGEN ATOM

In order to explain the empirical results obtained by Rydberg, Neils Bohr, in 1913, formulated a model of hydrogen atom utilizing classical physics and Planck's quantum theory. This semi classical theory is based on the following three postulates:

Postulate I: An electron, bound to the nucleus in an atom, can move around the nucleus in certain circular orbits without radiating. These orbits are called the discrete stationary states of the atom.

Postulate II: Only those stationary orbits are allowed for which orbital angular momentum is equal to an integral multiple of $\frac{h}{2\pi}$ i.e.,

$$mvr = \frac{nh}{2\pi} \quad \dots\dots\dots \quad (20.6)$$

where $n = 1, 2, 3, \dots\dots$ and n is called the principal quantum number, m and v are the mass and velocity of the orbiting electron respectively, and h is Planck's constant.

Postulate III: Whenever an electron makes a transition, that is, jumps from high energy state E_n to a lower energy state E_p, a photon of energy hf is emitted so that

$$hf = E_n - E_p \quad \text{..........} \quad (20.7)$$

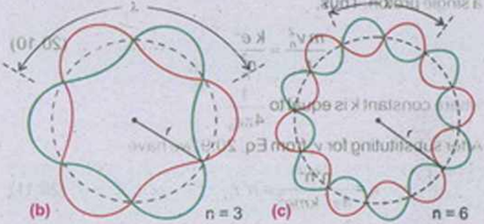
where $f = c/\lambda$ is the frequency of the radiation emitted.

Do You Know?

Helium was identified in the Sun using spectroscopy before it was discovered on earth.

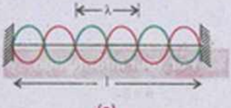
de-Broglie's Interpretation of Bohr's Orbits

At the time of formulation of Bohr's theory, there was no justification for the first two postulates, while Postulate III had some roots in Planck's thesis. Later on with the development of de Broglie's hypothesis, some justification could be seen in Postulate II as explained below.



(b) n = 3 (c) n = 6

Standing de Broglie waves of electrons around the circumference of Bohr orbits.



(a)

Fig. 20.3 Stationary wave for n = 3 on a string.

Consider a string of length ℓ as shown in Fig. 20.3 (a). If this is put into stationary vibrations, we must have $\ell = n\lambda$ where n is an integer. Suppose that the string is bent into circle of radius r, as demonstrated for n = 3 and n = 6 in Fig. 20.3 (b) and (c), so that

$$\ell = 2\pi r = n\lambda$$

or

$$\lambda = \frac{2\pi r}{n} \quad \text{..........} \quad (20.8)$$

From de Broglie's hypothesis

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

thus

$$\frac{h}{mv} = \frac{2\pi r}{n}$$

or

$$mvr = \frac{nh}{2\pi}$$

which is Postulate II.

Quantized Radii

Consider a hydrogen atom in which electron moving with velocity v_n is in stationary circular orbit of radius r_n. From Eq. (20.6),

$$v_n = \frac{nh}{2\pi m r_n} \qquad \text{..........} \qquad (20.9)$$

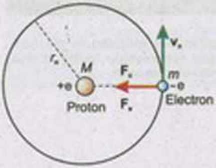


Fig. 20.4

For this electron to stay in the circular orbit, shown in Fig. 20.4, the centripetal force $F_c = \frac{mv_n^2}{r_n}$ is provided by the Coulomb's force $F_e = \frac{ke^2}{r_n^2}$, where e is the magnitude of charge on electron as well as on the hydrogen nucleus consisting of a single proton. Thus,

$$\frac{m v_n^2}{r_n} = \frac{k e^2}{r_n^2} \qquad \text{...........} \qquad (20.10)$$

where constant k is equal to $\frac{1}{4\pi\varepsilon_o}$.

After substituting for v_n from Eq. 20.9, we have

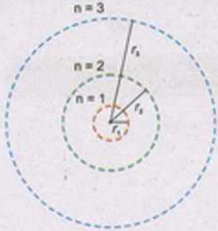
$$r_n = \frac{n^2 h^2}{4\pi^2 kme^2} = n^2 r_1 \qquad \text{...........} \qquad (20.11)$$

$$\text{where} \quad r_1 = \frac{h^2}{4\pi^2 kme^2} = 0.053\,\text{nm}$$

This agrees with the experimentally measured values and is called the first Bohr orbit radius of the hydrogen atom. Thus according to Bohr's theory, the radii of different stationary orbits of the electrons in the hydrogen atom are given by

$$r_n = r_1, 4r_1, 9r_1, 16r_1, \ldots\ldots$$

For Your Information



The first Bohr orbit in the hydrogen atom has a radius $r_1 = 5.3 \times 10^{-11}$ m. The second and third Bohr orbits have radii $r_2 = 4r_1$ and $r_3 = 9r_1$ respectively.

Substituting the value of r_n from Eq. 20.11 in Eq. 20.9, the speed of electron in the nth orbit is

$$v_n = \frac{2\pi ke^2}{nh} \qquad \text{..........} \qquad (20.12)$$

Quantized Energies

Let us now calculate the total energy E_n of the electron in the Bohr orbit; E_n is the sum of the kinetic energy K.E. and the potential energy U. i.e.,

$$E_n = \text{K.E.} + \text{U} = \frac{1}{2} mv_n^2 + \left(\frac{-ke^2}{r_n}\right) \qquad \text{..........} \qquad (20.13)$$

By rearranging Eq. (20.10), we get

$$\frac{1}{2}mv_n^2 = \frac{ke^2}{2r_n} \quad .... \quad (20.14)$$

then

$$E_n = \frac{ke^2}{2r_n} - \frac{ke^2}{r_n} = -\frac{ke^2}{2r_n} \quad .... \quad (20.15)$$

By substituting the value of r_n from Eq. (20.11), we have

$$E_n = -\frac{1}{n^2}\left(\frac{2\pi^2 k^2 me^4}{h^2}\right) = -\frac{E_o}{n^2} \quad .... \quad (20.16)$$

where

$$E_o = \frac{2\pi^2 k^2 me^4}{h^2} = \text{constant} = 13.6\text{ eV}$$

which is the energy required to completely remove an electron from the first Bohr orbit. This is called ionization energy. The ionization energy may be provided to the electron by collision with an external electron. The minimum potential through which this external electron should be accelerated so that it can supply the requisite ionization energy is known as ionization potential. Thus for n = 1, 2, 3,...... we get the allowed energy levels of a hydrogen atom to be

$$E_n = -E_o, -\frac{E_o}{4}, -\frac{E_o}{9}, -\frac{E_o}{16}, \ ......$$

The experimentally measured value of the binding energy of the electron in the hydrogen atom is in perfect agreement with the value predicted by Bohr theory.

Normally the electron in the hydrogen atom is in the lowest energy state corresponding to n = 1 and this state is called the ground state or normal state. When it is in higher orbit, it is said to be in the excited state. The atom may be exited by collision with externally accelerated electron. The potential through which an electron should be accelerated so that, on collision it can lift the electron in the atom from its ground state to some higher state, is known as excitation potential.

Hydrogen Emission Spectrum

The results derived above for the energy levels along with Postulate III can be used to arrive at the expression for the wavelength of the hydrogen spectrum. Suppose that the electron in the hydrogen atom is in the excited state n with

Do You Know?

The orbital electrons have specific amount of energies where as free electrons may have any amount of energy.

Do You Know?

Photon must have energy exactly equal to the energy difference between the two shells for excitation of an atom but an electron with K.E greater that the required difference can excite the gas atoms.

energy E_n and makes a transition to a lower state p with energy E_p, where $E_p < E_n$, then

$$hf = E_n - E_p$$

where $E_n = -\frac{E_o}{n^2}$ and $E_p = -\frac{E_o}{p^2}$

hence

$$hf = -E_o\left(\frac{1}{n^2} - \frac{1}{p^2}\right)$$

Substituting for $f = c/\lambda$ and rearranging

$$\frac{1}{\lambda} = \frac{E_o}{hc}\left(\frac{1}{p^2} - \frac{1}{n^2}\right)$$

or

$$\frac{1}{\lambda} = R_H\left(\frac{1}{p^2} - \frac{1}{n^2}\right) \quad \ldots\ldots\ldots \quad (20.17)$$

where R_H is the Rydberg constant given by the equation

$$R_H = \frac{E_o}{hc} = 1.0974 \times 10^7\ \text{m}^{-1} \quad \ldots\ldots\ldots \quad (20.18)$$

which agrees well with the latest measured value for hydrogen atom.

Eq. 20.17 reduces to the empirical result derived by Rydberg and given by Eq 20.1, provided that we substitute p = 2 and n = 3, 4, 5, ... The different energy levels corresponding to Eq. 20.17 are shown in Fig. 20.5.

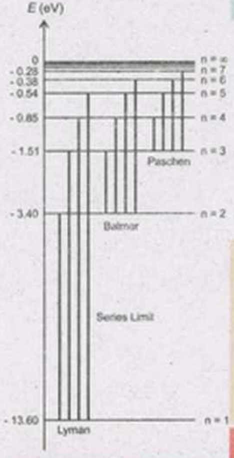


Fig. 20.5 Energy level diagram for the hydrogen atom.

Example 20.1: Find the speed of the electron in the first Bohr orbit.

Solution:

The speed found from Eq. (20.12) with n = 1, is

$$v_1 = \frac{2\pi ke^2}{h} = 2 \times 3.14 \times (9 \times 10^9\ \text{Nm}^2\text{C}^{-2})\left(\frac{(1.6 \times 10^{-19}\ \text{C})^2}{6.63 \times 10^{-34}\ \text{Js}}\right)$$

$$v_1 = 2.19 \times 10^6\ \text{ms}^{-1}$$

20.3 INNER SHELL TRANSITIONS AND CHARACTERISTIC X-RAYS

The transitions of electrons in the hydrogen or other light elements result in the emission of spectral lines in the infrared, visible or ultraviolet region of electromagnetic spectrum due to small energy differences in the transition levels.

In heavy atoms, the electrons are assumed to be arranged in concentric shells labeled as K, L, M, N, O etc., the K shell being closest to the nucleus, the L shell next, and so on (Fig. 20.6). The inner shell electrons are tightly bound and large amount of energy is required for their displacement from their normal energy levels. After excitation, when an atom returns to its normal state, photons of larger energy are emitted. Thus transition of inner shell electrons in heavy atoms gives rise to the emission of high energy photons or X-rays. These X-rays consist of series of specific wavelengths or frequencies and hence are called characteristic X-rays. The study of characteristic X-rays spectra has played a very important role in the study of atomic structure and the periodic table of elements.

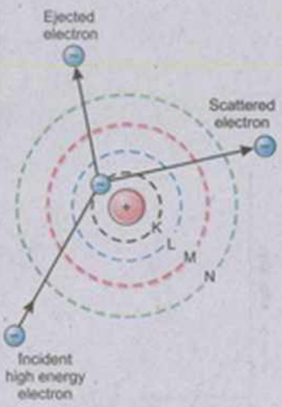


Fig. 20.6

Production of X-rays

Fig. 20.7 shows an arrangement of producing X-rays. It consists of a high vacuum tube called X-ray tube. When the cathode is heated by the filament F, it emits electrons which are accelerated towards the anode T. If V is the potential difference between C and T, the kinetic energy K.E. with which the electron strike the target is given by

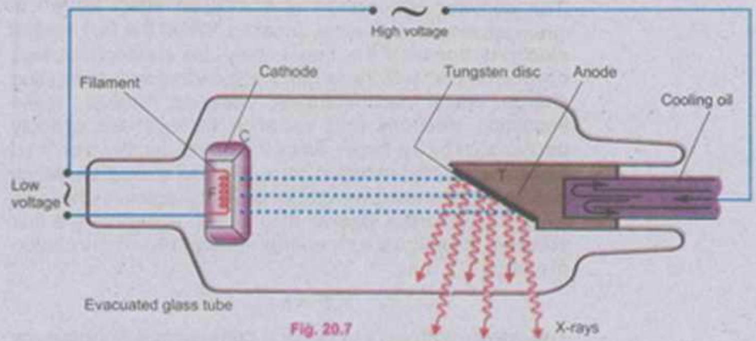


Fig. 20.7

$$K.E. = Ve \quad .... \quad (20.19)$$

Suppose that these fast moving electrons of energy *Ve* strike a target made of tungsten or any other heavy element. It is possible that in collision, the electrons in the innermost shells, such as K or L, will be knocked out. Suppose that one of the electrons in the K shell is removed, thereby producing a vacancy or hole in that shell. The electron from the L shell jumps to occupy the hole in the K shell, thereby emitting a photon of energy h $f_{K\alpha}$ called the K_α X-ray given by

$$h f_{K\alpha} = E_L - E_K \qquad \text{..........} \qquad (20.20)$$

It is also possible that the electron from the M shell might also jump to occupy the hole in the K shell. The photons emitted are K_β X-ray with energies

$$h f_{K\beta} = E_M - E_K \qquad \text{..........} \qquad (20.21)$$

these photons give rise to K_β X-ray and so on.

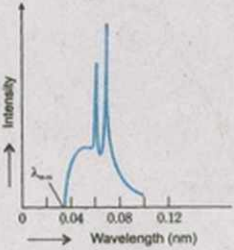


Fig. 20.8

The photons emitted in such transitions i.e., inner shell transitions are called characteristic X-rays, because their energies depend upon the type of target material.

The holes created in the L and M shells are occupied by transitions of electrons from higher states creating more X-rays. The characteristic X-rays appear as discrete lines on a continuous spectrum as shown in Fig. 20.8.

The Continuous X-ray Spectrum

The continuous spectrum is due to an effect known as bremsstrahlung or braking radiation. When the fast moving electrons bombard the target, they are suddenly slowed down on impact with the target. We know that an accelerating charge emits electromagnetic radiation. Hence, these impacting electrons emit radiation as they are strongly decelerated by the target. Since the rate of deceleration is so large, the emitted radiation correspond to short wavelength and so the bremsstrahlung is in the X-ray region. In the case when the electrons lose all their kinetic energy in the first collision, the entire kinetic energy appears as a X-ray photon of energy hf_{max}, i.e.,

$$\text{K.E.} = h f_{max}$$

The wavelength λ_{min} in Fig. 20.8 corresponds to frequency f_{max}. Other electrons do not lose all their energy in the first collision. They may suffer a number of collisions before coming to rest. This will give rise to photons of smaller energy or X-rays of longer wavelength. Thus the continuous spectrum is obtained due to deceleration of impacting electrons.

Properties and Uses of X-rays

X-rays have many practical applications in medicine and industry. Because X-rays can penetrate several centimetres into a solid matter, so they can be used to visualize the interiors of the materials opaque to ordinary light, such as fractured bones or defects in structural steel. The object to be visualized is placed between an X-ray source and a large sheet of photographic film; the darkening of the film is proportional to the radiation exposure. A crack or air bubble allows greater amount of X-rays to pass. This appears as a dark area on the photographic film. Shadow of bones appears lighter than the surrounding flesh. It is due to the fact that bones contain greater proportions of elements with high atomic number and so they absorb greater amount of incident X-rays than flesh. In flesh, light elements like carbon, hydrogen and oxygen predominate. These elements allow greater amount of incident X-rays to pass through them.

CAT - Scanner

In the recent past, several vastly improved X-ray techniques have been developed. One widely used system is computerized axial tomography;* the corresponding instrument is called CAT-Scanner. The X-ray source produces a thin fan-shaped beam that is detected on the opposite side of the subject by an array of several hundred detectors in a line. Each detector measures absorption of X-ray along a thin line through the subject. The entire apparatus is rotated around the subject in the plane of the beam during a few seconds. The changing reactions of the detector are recorded digitally; a computer processes this information and reconstructs a picture of different densities over an entire cross section of the subject. Density differences of the order of one percent can be detected with CAT-Scans. Tumors, and other anomalies much too small to be seen with older techniques can be detected.

Biological Effects of X-rays

X-rays cause damage to living tissue. As X-ray photons are absorbed in tissues, they break molecular bonds and create highly reactive free radicals (such as H and OH), which in turn can disturb the molecular structure of the proteins and especially the genetic material. Young and rapidly growing cells are particularly susceptible; hence X-rays are useful for selective destruction of cancer cells. On the other hand a cell may be damaged by radiation but survive, continue dividing and produce generation of defective cells. Thus X-rays can cause cancer. Even when the organism itself shows no apparent damage, excessive

For Your Information

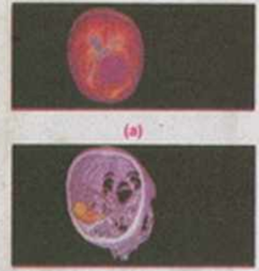
An X-ray picture of a hand.

Interesting Information

*In CAT scanning a "fanned-out" array of X-ray beams is directed through the patient from a number of different orientations.

radiation exposure can cause changes in their productiv system that will affect the organism's offspring.

Do You Know?



(a)

(b)

(a) This two-dimensional CAT scan of a brain reveals a large intracranial tumor (colored purple). (b) Three-dimensional CAT scans are now available and this example reveals an arachnoid cyst (colored yellow) within a skull. In both photographs the colors are artificial having been computer generated to aid in distinguishing anatomical features.

20.4 UNCERTAINTY WITHIN THE ATOM

One of the characteristics of dual nature of matter is fundamental limitation in the accuracy of the simultaneou measurement of the position and momentum of a particle.

Heisenberg showed that this is given by the equation

$$\Delta p \, \Delta x \geq \frac{h}{2\pi}$$

However, these limitations are significant in the realm o atom. One interesting question is whether electrons ar present in atomic nuclei. As the typical nuclei are less tha 10^{-14} m in diameter, for an electron to be confined within such nucleus, the uncertainty in its position is of the order of 10^{-14} The corresponding uncertainty in the electron's momentum

$$\Delta p \geq \frac{h}{\Delta x}$$

$$\geq \frac{6.63 \times 10^{-34}\ \text{Js}}{10^{-14}\text{m}} = 6.63 \times 10^{-20}\ \text{kg ms}^{-1}$$

As $$\Delta p = m \Delta v$$

Hence $$\Delta v = \frac{6.63 \times 10^{-20}\ \text{kg ms}^{-1}}{9.11 \times 10^{-31}\ \text{kg}} \geq 7.3 \times 10^{10}\ \text{ms}^{-1}$$

Hence, for the electron to be confined to a nucleus, its spee would have to be greater than 10^{10} ms^{-1} i.e., greater than the speed of light. Because this is impossible, we must conclude that an electron can never be found inside of a nucleus. Bu can an electron reside inside the atom? To find this, we again calculate the speed of an electron and if it turns to be less than the speed of light, we have reasonable expectation o finding the electron within the atom but outside the nucleus. The radius of the hydrogen atom is about 5×10^{-11} m. Applying the uncertainty principle to the momentum of electron in the atom we have

$$\Delta p \geq \frac{h}{\Delta x}$$

As $$\Delta p = m \Delta v$$

Therefore, $$\Delta v = \frac{h}{m \Delta x}$$

For an atom Δx is given as 5×10^{-11} m

Thus
$$\Delta v = \frac{6.63\times10^{-34}\ \text{Js}}{9.11\times10^{-31}\ \text{kg}\times5\times10^{-11}\ \text{m}}$$

$$= 1.46\times10^{7}\ \text{ms}^{-1}$$

This speed of the electron is less than the speed of light, herefore, it can exist in the atom but outside the nucleus.

20.5 LASER

Laser is the acronym for Light Amplification by Stimulated Emission of Radiation. As the name indicates, lasers are used for producing an intense, monochromatic, and unidirectional coherent beam of visible light. To understand he working of a laser, terms such as stimulated emission and population inversion must be understood.

Spontaneous and Stimulated Emissions

Consider a sample of free atoms some of which are in the ground state with energy E_1 and some in the excited state E_2 s shown in Fig. 20.9. The photons of energy h$f = E_2 - E_1$ are ncident on this sample. These incident photons can interact with atoms in two different ways. In Fig. 20.9 (a) the incident photon is absorbed by an atom in the ground state E_1, thereby eaving the atom in the excited state E_2. This process is called timulated or induced absorption. Once in the excited state, wo things can happen to the atom. (i) It may decay by pontaneous emission as shown in Fig. 20.9 (b), in which the tom emits a photon of energy h $f = E_2 - E_1$ in any arbitrary irection.

(a) Induced absorption

(b) Spontaneous emission

(c) Induced emission

Fig 20.9

he other alternative for the atom in the excited state E_2 is to ecay by stimulated or induced emission as shown in ig.20.9 (c). In this case the incident photon of energy $f = E_2 - E_1$ induces the atom to decay by emitting a photon hat travels in the direction of the incident photon. For each ncident photon we will have two photons going in the same irection thus we have accomplished two things; an amplified s well as a unidirectional coherent beam. From a practical oint this is possible only if there is more stimulated or nduced emission than spontaneous emission. This can be chieved as described in the next section.

Population Inversion and Laser Action

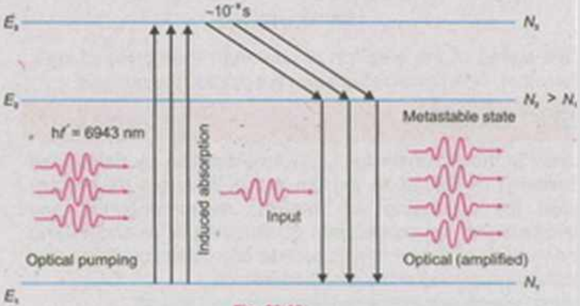
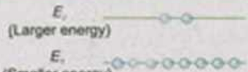


Fig. 20.10

Let us consider a simple case of a material whose atoms can reside in three different states as shown in Fig. 20.10, state E_1 which is ground state; the excited state E_3, in which the atoms can reside only for 10^{-8} s and the metastable state E_2, in which the atoms can reside for $\sim 10^{-3}$ s, much longer than 10^{-8} s. A metastable state is an excited state in which an excited electron is unusually stable and from which the electron spontaneously falls to lower state only after relatively longer time. The transition from or to this state are difficult as compared to other excited states. Hence, instead of direct excitation to this state, the electrons are excited to higher level for spontaneous fall to metastable state. Also let us assume that the incident photons of energy $hf = E_3 - E_1$ raise the atom from the ground state E_1 to the excited state E_3 but the excited atoms do not decay back to E_1. Thus the only alternative for the atoms in the excited state E_3 is to decay spontaneously to state E_2, the atoms reach state E_2 much faster than they leave state E_2. This eventually leads to the situation that the state E_2 contains more atoms than state E_1. This situation is known as population inversion.

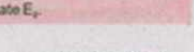
Once the population inversion has been reached, the lasing action of a laser is simple to achieve. The atoms in the metastable state E_2 are bombarded by photons of energy $hf = E_2 - E_1$, resulting in an induced emission, giving an intense, coherent beam in the direction of the incident photon.

For Your Information



(a) **Normal population**

A normal population of atomic energy state, with more atomic in the lower energy state E_1 than in the excited state E_2.



(b) **Population inversion**

A population inversion, in which the higher energy state has a greater population than the lower energy state.

The emitted photons must be confined in the assembly long enough to stimulate further emission from other excited atoms. This is achieved by using mirrors at the two ends of the assembly. One end is made totally reflecting, and the other end is partially transparent to allow the laser beam to escape (Fig.20.11). As the photons move back and forth between the reflecting mirrors they continue to stimulate other excited atoms to emit photons. As the process continues the number of photons multiply, and the resulting radiation is, therefore, much more intense and coherent than light from ordinary sources.

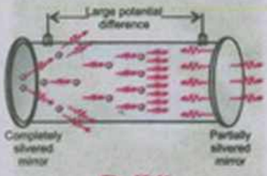


Fig. 20.11

Helium - Neon Laser

It is a most common type of lasers used in physics laboratories. Its discharge tube is filled with 85% helium and 15% neon gas. The neon is the lasing or active medium in this tube. By chance, helium and neon have nearly identical metastable states, respectively located 20.61 eV and 20.66 eV level. The high voltage electric discharge excites the electrons in some of the helium atoms to the 20.61 eV state. In this laser, population inversion in neon is achieved by direct collisions with same energy electrons of helium atoms. Thus excited helium atoms collide with neon atoms, each transferring its own 20.61 eV of energy to an electron in the neon atom along with 0.05 eV of K.E. from the moving atom. As a result, the electrons in neon atoms are raised to the 20.66 eV state. In this way, a population inversion is sustained in the neon gas relative to an energy level of 18.70 eV. Spontaneous emission from neon atoms initiate laser action and stimulated emission causes electrons in the neon to drop from 20.66 eV to the 18.70 eV level and red laser light of wavelength 632.8 nm corresponding to 1.96 eV energy is generated (Fig. 20.12).

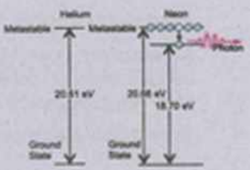


Fig. 20.12

Uses of Laser in Medicine and Industry

1. Laser beams are used as surgical tool for "welding" detached retinas.
2. The narrow intense beam of laser can be used to destroy tissue in a localized area. Tiny organelles with a living cell have been destroyed by using laser to study how the absence of that organelle affects the behavior of the cell.
3. Finely focused beam of laser has been used to destroy cancerous and pre-cancerous cell.

4. The heat of the laser seals off capillaries and lymph vessels to prevent spread of the disease.

5. The intense heat produced in small area by a laser beam is also used for welding and machining metals and for drilling tiny holes in hard materials.

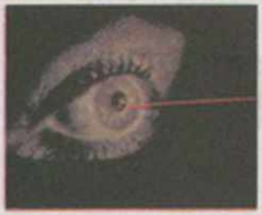
6. The precise straightness of a laser beam is also useful to surveyors for lining up equipment especially in inaccessible locations.

7. It is potential energy source for inducing fusion reactions.

8. It can be used for telecommunication along optical fibres.

9. Laser beam can be used to generate three-dimensional images of objects in a process called holography.

Do You Know?



The helium-neon laser beam is being used to diagnose diseases of the eye. The use of laser technology in the field of ophthalmology is widespread.

SUMMARY

- When an atomic gas or vapours at less than atmospheric pressure is suitably excited, usually by passing electric current through it, the emitted radiation has a spectrum which contains certain specific wavelenghts only.
- Postulates of Bohr's model of hydrogen atom are:

i. An electron, bound to the nucleus in an atom, can move around the nucleus in certain circular orbits without radiating. These orbits are called the discrete stationary states of the atom.

ii. Only those stationary states are allowed for which orbital angular momentum is equal to an integral multiple of h i.e., $mvr = \frac{nh}{2\pi}$

iii. Whenever an electron makes a transition, i.e., jumps from high energy state E_n to a lower energy state E_p, a photon of energy hf is emitted so that $hf = E_n - E_p$.

- The transition of electrons in the hydrogen or other light elements result in the emission of spectral lines in the infrared, visible or ultraviolet region of electromagnetic spectrum due to small energy differences in the transition levels.
- The X-rays emitted in inner shell transitions are called characteristic X-rays, because their energy depends upon the type of target material.
- The X-rays that are emitted in all directions and with a continuous range of frequencies are known as continuous X-rays.
- Laser is the acronym for Light Amplification by Stimulated Emission of Radiation.

- The incident photon absorbed by an atom in the ground state E_1, thereby leaving the atom in the excited state E_2 is called stimulated or induced absorption.
- Spontaneous or induced emission is that in which the atom emits a photon of energy $hf = E_2 - E_1$ in any arbitrary direction.
- Stimulated or induced emission is that in which the incident photon of energy $hf = E_2 - E_1$ induces the atom to decay by emitting a photon that travels in the direction of the incident photon. For each incident photon, we will have two photons going in the same direction giving rise to an amplified as well as a unidirectional coherent beam.

QUESTIONS

20.1 Bohr's theory of hydrogen atom is based upon several assumptions. Do any of these assumptions contradict classical physics?

20.2 What is meant by a line spectrum? Explain, how line spectrum can be used for the identification of elements?

20.3 Can the electron in the ground state of hydrogen absorb a photon of energy 13.6 eV and greater than 13.6 eV?

20.4 How can the spectrum of hydrogen contain so many lines when hydrogen contains one electron?

20.5 Is energy conserved when an atom emits a photon of light?

20.6 Explain why a glowing gas gives only certain wavelengths of light and why that gas is capable of absorbing the same wavelengths? Give a reason why it is transparent to other wavelengths?

20.7 What do we mean when we say that the atom is excited?

20.8 Can X-rays be reflected, refracted, diffracted and polarized just like any other waves? Explain.

20.9 What are the advantages of lasers over ordinary light?

20.10 Explain why laser action could not occur without population inversion between atomic levels?

PROBLEMS

20.1 A hydrogen atoms is in its ground state (n = 1). Using Bohr's theory, calculate (a) the radius of the orbit, (b) the linear momentum of the electron, (c) the angular momentum of the electron (d) the kinetic energy (e) the potential energy, and (f) the total energy.

[Ans: (a) 0.529×10^{-10} m (b) 1.99×10^{-24} kg ms^{-1} (c) 1.05×10^{-34} kg m^{2}s^{-1}
(d) 13.6 eV (e) - 27.2 eV (f) -13.6 eV]

20.2 What are the energies in eV of quanta of wavelength? $\lambda = 400, 500$ and 700 nm.
(Ans: 3.10 eV, 2.49 eV, 1.77 eV)

20.3 An electron jumps from a level $E_i = -3.5 \times 10^{-19}$ J to $E_f = -1.20 \times 10^{-19}$ J. What is the wavelength of the emitted light? **(Ans:** 234 nm)

20.4 Find the wavelength of the spectral line corresponding to the transition in hydrogen from n = 6 state to n = 3 state?
(Asn: 1094 nm)

20.5 Compute the shortest wavelength radiation in the Balmer series? What value of n must be used? **(Ans:** 364.5 nm, $n = \infty$)

20.6 Calculate the longest wavelength of radiation for the Paschen series.
(Ans: 1875 nm)

20.7 Electrons in an X-ray tube are accelerated through a potential difference of 3000 V. If these electrons were slowed down in a target, what will be the minimum wavelength of X-rays produced? **(Ans:** 4.14×10^{-10} m)

20.8 The wavelength of K X-ray from copper is 1.377×10^{-10} m. What is the energy difference between the two levels from which this transition results?
(Ans: 9.03 keV)

20.9 A tungsten target is struck by electrons that have been accelerated from rest through 40 kV potential difference. Find the shortest wavelength of the bremsstrahlung radiation emitted. **(Ans:** 0.31×10^{-10} m)

20.10 The orbital electron of a hydrogen atom moves with a speed of 5.456×10^5 ms^{-1}.
(a) Find the value of the quantum number n associated with this electron.
(b) Calculate the radius of this orbit.
(c) Find the energy of the electron in this orbit.
(Ans: n = 4, $r_4 = 0.846$ nm; $E_4 = -0.85$ eV)