Chapter 6

Spectrum

SYLLABUS

Using a triangular prism to produce a visible spectrum from white light; Electromagnetic spectrum. Scattering of light.

Scope of syllabus : Deviation produced by a triangular prism; dependence on colour (wavelength) of light; dispersion and spectrum; electromagnetic spectrum; broad classification (names only arranged in order of increasing wavelength); properties common to all electromagnetic radiations; properties and uses of infrared and ultraviolet radiations. Simple application of scattering of light e.g. blue colour of the sky.

(A) DEVIATION, DISPERSION AND SPECTRUM

6.1 DEVIATION PRODUCED BY A TRIANGULAR PRISM

Read for revision

Fig. 6.1 shows the deviation produced by a triangular prism for a light ray. When a light ray PQ of a single colour enters a triangular prism ABC, it gets deviated, say, by an angle δ_1 towards the base BC at the first surface AB of the prism and travels straight as QR inside the prism. The angle of deviation δ_1 depends on the angle of incidence and the refractive index of glass with respect to air. On striking the second surface AC, the ray QR gets further deviated, say, by an angle δ_2 towards the base BC and travels straight as RS outside the prism. The angle of deviation δ_2 depends on the angle of incidence at the second surface (which depends on the angle of the prism A) and the refractive index of air with respect to glass. For the emergent ray RS, the total deviation δ with respect to the incident ray PQ (*i.e.*, the angle between the emergent ray RS and the direction PL of the incident ray PQ) is given as :

$$\boxed{\delta = \delta_1 + \delta_2} \quad ...(6.1)$$

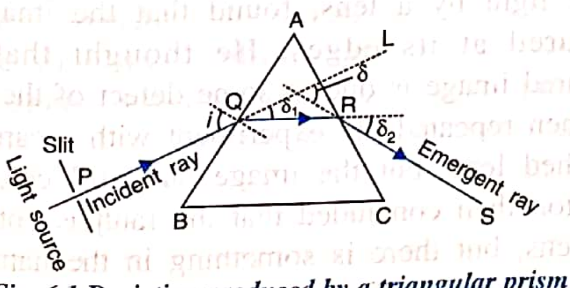

Fig. 6.1 Deviation produced by a triangular prism

The total angle of deviation δ, thus depends upon the following *three* factors :

(1) the angle of incidence (i) at the first surface,

(2) the angle of the prism (A), and

(3) the refractive index of the material of the prism (μ). Since the refractive index depends on the colour (or wavelength λ) of the light used, so the angle of deviation depends also on the colour (or wavelength λ) of the incident light.

In chapter 4, we have discussed for light of single colour the dependence of angle of deviation δ on the angle of incidence i, angle of prism A and refractive index μ of the material of prism. Here we shall discuss in detail how the deviation δ produced by a prism depends on the colour (or wavelength λ) of the incident light.

Dependence of deviation on the colour (or wavelength) of light

Light of different colours have the same speed in air but different speeds in a medium other than air. If the light entering a prism is not of a single colour, *i.e.*, it is a mixture of several colours, then the emergent beam too has different colours arranged in a *definite order*. It is so because the speed of light in a transparent medium decreases with the decrease in the wavelength of light. Since, *the refractive index of glass* (the material of prism) *increases with the decrease in the wavelength of light*, therefore the deviation caused by a prism also increases with the decrease in the wavelength of light*. ***In visible light, violet colour (wavelength λ ≃ 4000 Å) is deviated the most and red colour (wavelength λ ≃ 8000 Å) is deviated the least*** because in glass, the speed of violet light is the least and that of red light is the most.

6.2 COLOURS IN WHITE LIGHT WITH THEIR WAVELENGTH AND FREQUENCY RANGE

The white light emitted from a source consists of light of different wavelengths. The light of different wavelengths produce the sensation of different colours on the retina of our eye, so we perceive them as different colours. The prominent colours in white light are violet, indigo, blue, green, yellow, orange and red. Different colours differ in their wavelength. In fact, *wavelength is the characteristic of colour, irrespective of its origin i.e.*, light of the same colour obtained from different sources will have the same wavelength.

* From the definition of refractive index

$$\mu_{glass} = \frac{\text{Speed of light in air}}{\text{Speed of light in glass}}$$

The speed of light for different colours is the same in air, but it is different for different colours in glass (medium). In glass, the speed of violet light is *minimum* and the speed of red light is *maximum*. Therefore $\mu_{violet} > \mu_{red}$

But $\mu = \sin i / \sin r$ or $\sin r = \sin i / \mu$

Therefore, in glass, for a given value of i, the angle of refraction r is minimum for the light of violet colour and maximum for the light of red colour *i.e.*, $r_{red} > r_{violet}$.

Now angle of deviation $\delta = i - r$, so $\delta_{violet} > \delta_{red}$

In other words, colour is the *subjective property* of light related to its wavelength.

The table below gives the range of wavelength and frequency for light of different colours present in the white light.

Wavelength and frequency of different colours in white light

Colour	Wavelength (λ) range (nearly)	Frequency ($\nu = c/\lambda$) range in 10^{14} Hz
Violet	4000 Å to 4460 Å	7·5 – 6·73
Indigo	4460 Å to 4640 Å	6·73 – 6·47
Blue	4640 Å to 5000 Å	6·47 – 6·01
Green	5000 Å to 5780 Å	6·01 – 5·19
Yellow	5780 Å to 5920 Å	5·19 – 5·07
Orange	5920 Å to 6200 Å	5·07 – 4·84
Red	6200 Å to 8000 Å	4·84 – 3·75

Note : **(1)** In the above table the letter Å denotes the unit Angstrom where 1 Å = 10^{-10} m (or 10^{-8} cm). Nowadays wavelength is expressed mostly in nanometre (nm) where

Read

$$1 \text{ nm} = 10^{-9} \text{ m} = 10 \text{ Å}.$$

(2) In the spectrum of white light, red colour has the longest wavelength 8000 Å (or 8×10^{-7}m or 800 nm) or lowest frequency $3·75 \times 10^{14}$ Hz and violet colour has the shortest wavelength 4000 Å (or 4×10^{-7}m or 400 nm) or highest frequency $7·5 \times 10^{14}$ Hz. From the violet end to the red end of the spectrum, the wavelength increases while the frequency decreases.

6.3 DISPERSION OF WHITE LIGHT THROUGH A PRISM AND FORMATION OF A SPECTRUM

Sir Isaac Newton, while studying the image of a heavenly body formed due to refraction of white light by a lens, found that the image is coloured at its edges. He thought that the coloured image is due to some defect of the lens. He then repeated the experiment with a carefully polished lens, but the image was still coloured. Newton then concluded that the fault is not with the lens, but there is something in the nature of white light itself due to which the image is coloured at its edges. To investigate it further, he performed another experiment with a *prism*.

Newton's Experiment

Newton allowed the white light from the Sun to enter a dark room through a small aperture in a window and placed a glass prism in the path of the light rays. The light emerging out of the prism was received on a white screen. On the screen, a coloured patch like that of a rainbow as shown in Fig. 6.2 was obtained which was termed as *spectrum*.

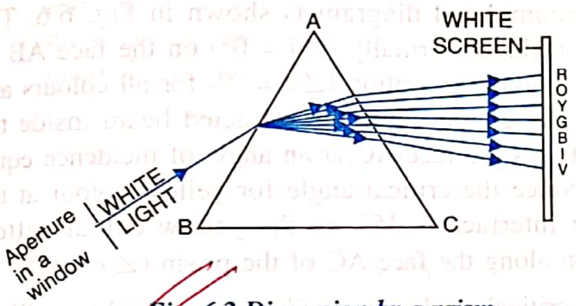

Fig. 6.2 Dispersion by a prism

Starting from the side of the base of the prism, the order of colours in the spectrum on the screen is :

Violet, Indigo, Blue, Green, Yellow, Orange, and *Red*. This order of colours in the spectrum can easily be remembered by the word ***VIBGYOR***.

Conclusion : Read From the above experiment, Newton concluded that *white light consists of seven prominent colours*. Each colour corresponds to a small range of wavelength. Thus, white light is a mixture of large number of wavelengths *i.e.*, it is *polychromatic* in nature.

> *Note :* In the spectrum, each colour is mixed with the other colour *i.e., there is no sharp boundary line separating the colours*. In the diagram, colours are shown widely separated just for clarity. The total spread of colours is much less than that shown in the diagram. Different colours have different width on the screen.

Dispersion

> The phenomenon of splitting of white light by a prism into its constituent colours is known as dispersion.

Spectrum

> On passing white light through a prism, the band of colours seen on a screen is called the spectrum.

Cause of dispersion of white light and formation of spectrum

The cause of dispersion of white light is that lights of different wavelengths travel with different speeds in a medium. When white light enters the first surface of a prism, lights of different colours due to their different speeds in glass, get deviated through different angles towards the base of the prism i.e. the dispersion (or splitting) of white light into its constituent colours takes place at the first surface of the prism. Violet colour is deviated the most, while red colour is deviated the least. Therefore light of different colours present in white light follow different paths inside the glass prism and then strike the second surface of the prism. On the second surface of the prism, *only refraction takes place* (from glass to air) and different colours are deviated through different angles due to their different angles of incidence at this surface. Here again violet is deviated the most and red the least. As a result, the colours get further separated on refraction at the second surface. The light emerging out of the prism, thus, has different colours that spread out to form a spectrum on the screen.

> *Note :* (1) Dispersion of white light occurs only at the first surface of a prism.
>
> (2) Deviation of light rays occurs at both the surfaces of a prism.
>
> (3) A prism does not produce colours, but it only splits the various colours present in the light incident on it.

(a) Which colour has greater speed in vacuum ?

(b) Which colour has greater speed in glass ?

Ans. (a) In vacuum, both have the same speeds.
(b) In glass, red light has a greater speed.

13. Define the term dispersion of light.

14. Explain the cause of dispersion of white light through a prism.

15. Explain briefly, with the help of a neat labelled diagram, how does white light get dispersed by a prism.

On which surface of a prism, there is both dispersion and deviation of light, and on which surface of the prism, there is only deviation of light ?

Ans. (i) on first surface, (ii) on second surface

16. What do you understand by the term spectrum ?

17. A ray of white light is passed through a glass prism and a spectrum is obtained on a screen.

(a) Name the seven colours of the spectrum in order.

(b) Do the colours have the same width in the spectrum ?

(c) Which colour of the spectrum of white light deviates (i) the most, (ii) the least ?

18. The diagram shown below in Fig. 6.8 shows the path taken by a narrow beam of yellow monochromatic light passing through an equiangular glass prism. If the yellow light is replaced by a narrow beam of white light incident at the same angle, draw another diagram to show the passage of white light through the prism and label it to show the effect of the prism on the white light.

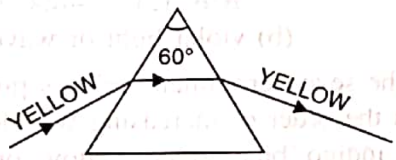

Fig. 6.8

19. Fig. 6.9 shows a thin beam of white light from a source S striking on one face of a prism.

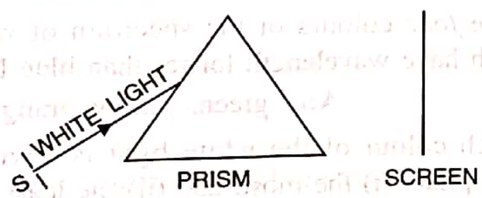

Fig. 6.9

(a) Complete the diagram to show the effect of the prism on the beam and to show what is seen on the screen.

(b) If a slit is placed in between the prism and the screen to pass only the light of green colour, what will you then observe on the screen ?

(c) What conclusion do you draw from the observation in part (b) above ?

20. (a) A beam of monochromatic light undergoes minimum deviation through an equiangular prism. How does the beam pass through the prism with respect to its base ?

(b) If white light is used in the same way as in part (a) above, what change do you expect in the emergent beam ?

(c) What conclusion do you draw about the nature of white light in part (b) ?

Ans. (a) parallel to the base, (b) white light splits into its constituent colours *i.e.*, spectrum is formed (c) white light is polychromatic

MULTIPLE CHOICE TYPE

1. When a white light ray falls on a prism, the ray at its first surface suffers :

(a) no refraction

(b) only dispersion

(c) only deviation

(d) both deviation and dispersion.

Ans. (d) both deviation and dispersion.

2. In the spectrum of white light by a prism, the colour at the extreme end opposite to the base of prism is :

(a) violet (b) yellow

(c) red (d) blue.

Ans. (c) red

3. The wavelength range of white light is :

(a) 4000 nm to 8000 nm

(b) 40 nm to 80 nm

(c) 400 nm to 800 nm

(d) 4 nm to 8 nm.

Ans. (c) 400 nm to 800 nm

NUMERICALS

Solve

1. Calculate the frequency of yellow light of wavelength 550 nm. The speed of light is 3×10^8 m s^{-1}.

Ans. $5{\cdot}4 \times 10^{14}$ Hz

2. The frequency range of visible light is from $3{\cdot}75 \times 10^{14}$ Hz to $7{\cdot}5 \times 10^{14}$ Hz. Calculate its wavelength range. Take speed of light $= 3 \times 10^8$ m s^{-1}.

Ans. 4000 Å to 8000 Å

(B) ELECTROMAGNETIC SPECTRUM AND ITS BROAD CLASSIFICATION

6.4 ELECTROMAGNETIC SPECTRUM

Classification : Till now we have limited ourselves to the spectrum of white light which lies between the red and the violet regions. This spectrum is the *visible spectrum* and it is only a very small part of the entire electromagnetic spectrum. Experiments show that the spectrum of radiation from the sun is limited not only between the violet and red extremes, but it extends on either side beyond these extremes to which our eyes do not respond. *The part of spectrum beyond the red extreme and the violet extreme is called the* ***invisible spectrum****.

The waves of wavelength longer than the red part of the visible spectrum in increasing order of wavelength are (i) *infrared radiations*, (ii) *microwaves*, and (iii) *radio waves*, while the waves of wavelength shorter than the violet part of the visible spectrum in decreasing order of wavelength are : (i) *ultraviolet rays*, (ii) *X-rays*, and (iii) *gamma rays*. These radiations together form the electromagnetic spectrum.

Read

The complete electromagnetic spectrum *in increasing order of their wavelengths* (or *decreasing order of their frequencies*) is given below :

(1) Gamma rays, (2) X-rays, (3) Ultraviolet rays, (4) Visible light, (5) Infrared radiations, (6) Microwaves, and (7) Radio waves.

These electromagnetic waves are of different wavelengths, but they have properties similar to the light waves. Each wave travels with the same speed equal to 3×10^8 m s^{-1} in vacuum (or air).

The speed (c), frequency (f) and wavelength (λ) of electromagnetic waves are related as :

$$\boxed{c = f\lambda} \quad ....(6.2)$$

The complete electromagnetic spectrum is shown in Fig. 6.10 with the wavelength increasing towards the right side (or frequency increasing towards the left side).

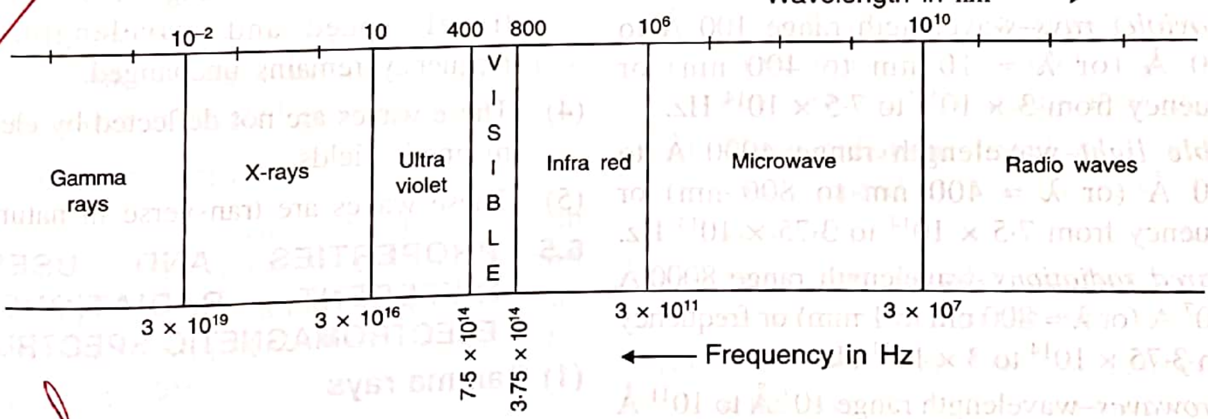

Fig. 6.10 Electromagnetic spectrum

Read

Note : (1) In Fig. 6.10, although we have shown a boundary line in between different waves, but there is no sharp boundary of wavelength (or frequency) between two successive electromagnetic waves. In fact, they overlap to a good extent.

(2) The infrared spectrum is the part of spectrum just beyond the red end, while the ultraviolet spectrum is the part of spectrum just before the violet end.

* The portion of electromagnetic waves other than the visible part, do not excite our retina to produce the sensation of vision. However, some electromagnetic waves can damage the retina.

The table below shows the different waves of the electromagnetic spectrum in order of their increasing wavelengths alongwith their discoverer, source and method of detection.

Electromagnetic spectrum

Name of the wave	Wavelength in nm	Discoverer	Source	Method of detection
Gamma rays	below 0·01	Becquerel & Curie	In cosmic rays, from radioactive substances.	By their large penetrating power
X-rays	0·01 – 10	Roentgen	From a heavy metal target of high melting point when highly energetic electrons are stopped by it.	By the fluorescence produced on a zinc sulphide screen. The photographic film gets affected.
Ultraviolet	10 – 400	Ritter	Sunlight, arc-lamp, spark	By their chemical activity on dyes. Photographic plates get affected. It causes fluorescence.
Visible light	400 – 800	Newton	Sunlight, light from electric bulb, flame, white hot bodies.	Other objects can be seen in its presence.
Infrared waves	$800 - 10^6$	Hershell	Lamp with thoriated filament, heated silicon carbide rod, red hot bodies	Heating effect is more. The mercury rises rapidly when a thermometer with a blackened bulb is kept in these radiations.
Microwaves	$10^6 - 10^{10}$	Hertz	Electronic devices such as crystal oscillators	Oscillatory electrical circuit.
Radio waves	above 10^{10}	Marconi	TV and radio transmitters	Aerials of radio and TV receiver.

Approximate ranges of wavelength and frequency

(1) *Gamma rays*–wavelength shorter than 0·1 Å (or λ < 0·01 nm) or frequency above 10^{19} Hz.

(2) *X-rays*–wavelength range 0·1 Å to 100 Å (or $\lambda \approx$ 0·01 nm to 10 nm) or frequency from 3×10^{19} to 3×10^{16} Hz.

(3) *Ultraviolet rays*–wavelength range 100 Å to 4000 Å (or $\lambda \approx$ 10 nm to 400 nm) or frequency from 3×10^{16} to $7{\cdot}5 \times 10^{14}$ Hz.

(4) *Visible light*–wavelength range 4000 Å to 8000 Å (or $\lambda \approx$ 400 nm to 800 nm) or frequency from $7{\cdot}5 \times 10^{14}$ to $3{\cdot}75 \times 10^{14}$ Hz.

(5) *Infrared radiations*–wavelength range 8000 Å to 10^7 Å (or $\lambda \approx$ 800 nm to 1 mm) or frequency from $3{\cdot}75 \times 10^{14}$ to 3×10^{11} Hz.

(6) *Microwaves*–wavelength range 10^7 Å to 10^{11} Å (or $\lambda \approx$ 1 mm to 10 m) or frequency from 3×10^{11} to 3×10^7 Hz.

(7) *Radio waves*–wavelength above 10^{11} Å (or λ > 10 m) or frequency below 3×10^7 Hz.

All Imp

Properties common to all electromagnetic waves

(1) Electromagnetic waves do not require any material medium for their propagation.

(2) They all travel with the same speed in vacuum and air (the speed is 3×10^8 m s^{-1}), and with different speeds in different medium.

(3) They exhibit the properties of reflection and refraction. In refraction, when an electromagnetic wave passes from one medium to the other, there is change in its direction of travel, speed and wavelength, but its frequency remains unchanged.

(4) These waves are not deflected by electric and magnetic fields.

(5) These waves are transverse in nature.

6.5 PROPERTIES AND USES OF DIFFERENT RADIATIONS OF ELECTROMAGNETIC SPECTRUM

(1) Gamma rays

These are the most energetic electromagnetic radiations of wavelength less than 0·1 Å (or 0·01 nm).

Sources : They are obtained in radioactive emissions, when the nuclei of radioactive atoms pass from the excited state to the ground state. They are also present in cosmic radiations.

Properties : Like X-rays, they cause fluorescence when they strike the fluorescent