Pearson Physics Level 30
Unit VII Electromagnetic Radiation: Unit VII Review Solutions

Student Book pages 746–749

Vocabulary

1. **angle of diffraction:** the angle formed between the perpendicular bisector and the straight line to a nodal or antinodal point on the interference pattern
   antinode: a point of interaction between waves, at which only constructive interference occurs
   blackbody: an object that completely absorbs any light energy that falls on it
   blackbody radiation curve: a graph of the intensity of light emitted versus wavelength for an object of a given temperature
   Compton effect: the change in wavelength of the scattered X ray photon
   Compton scattering: the scattering of an X ray by an electron
   converging: the process whereby refracted or reflected rays converge or meet at a single point
   critical angle: for any two media, the size of the incident angle for which the angle of refraction is 90°
   diffraction: the change in shape and direction of a wave front as a result of encountering a small opening or aperture in a barrier, or a corner
   diffraction grating: a sheet of glass or plastic etched with a large number of parallel lines; when light is incident on the grating, each line or slit acts as one individual light source
   dispersion: separation of white light into its components
   diverging: the process whereby refracted or reflected rays are spread out such that they never meet at a single point
   electromagnetic wave (radiation): periodic variation in perpendicular electric and magnetic fields, propagating at right angles to both fields
   focal point (F)**:** the point where light rays that are parallel to and close to the principal axis converge, or appear to diverge from, after being reflected or refracted
   frequency (f)**:** number of cycles per unit of time
   Heisenberg's uncertainty principle: It is impossible to know both the position and momentum of a particle with unlimited precision at the same time.
   Huygens' Principle: a model of wave theory, which predicted the motion of a wave front as being many small point sources propagating outward in a concentric circle at the same speed as the wave itself
   image attitude: the orientation characteristic of an image, whether erect or inverted
   incandescent: glowing with heat
   interference: an effect resulting from the passage of two like waves through each other
   law of reflection: the angle of reflection is equal to the angle of incidence
   magnification (m)**:** the relationship of the size of the image to the size of the object

node: a point of interaction between waves, at which only destructive interference occurs
particle model: describes electromagnetic radiation as a stream of tiny particles radiating out from a source
path length: the distance between a point source and a chosen point in space
period (*T*)**:** time required to complete one cycle
photoelectric effect: the emission of electrons when a metal is illuminated by short wavelengths of light
photoelectrons: electrons emitted from a metal because of the photoelectric effect
photon: a quantum of light
Planck's formula: Light comes in quanta of energy that can be calculated using the formula $E = nhf$, where h is a constant of proportionality having the value of 6.63×10^{-34} J·s.
polarization: production of a state in which the plane of the electric field for each electromagnetic wave occurs in only one direction
quantized: limited to whole multiples of a basic amount, the quantum
quantum: the smallest amount or "bundle" of energy that a wavelength of light can possess
quantum indeterminacy: the probability of finding a particle at a particular location in a double-slit interference pattern
refraction: a change in the direction of light as it passes at an angle from one medium to another
refractive index (*n*)**:** a ratio comparing the speed of light in a vacuum to the measured speed of light in a medium
Snell's Law: for any angle of incidence greater than zero, the ratio $\sin\theta_i / \sin\theta_r$ is a constant for any light ray passing through the boundary between two media
spectrum: the bands of colours making up white light; in order: red, orange, yellow, green, blue, and violet
stopping potential: the potential difference for which the kinetic energy of a photoelectron equals the work needed to move through a potential difference, V
threshold frequency: the minimum frequency that a photon can have to cause photoemission from a metal
total internal reflection: reflection of all incident light back into the medium that has the higher refractive index
wave model: describes electromagnetic radiation as a stream of transverse waves radiating out from a source
wave-particle duality: light has both wave-like and particle-like properties
wavelength (λ)**:** the distance between adjacent points that vibrate in phase with one another in a wave
work function: the minimum energy that a photon can have to cause photoemission from a metal. The work function is specific for every metal.

Knowledge

Chapter 13

2. The currently accepted quantum model describes light and all other radiation as discrete bundles or "packets" of energy. Each packet, or photon, is a particle that has wave characteristics. In the quantum model, EMR has two aspects of behaviour, one being wavelike and the other being particle-like.

3. According to Ampere's Law, if the magnetic field changes over time, then there must be a current flowing. But according to the classical laws of physics, current flow was not possible in empty space, in the absence of a conductor. However, Maxwell observed that the electric field produced by a capacitor could actually have the same effect as a moving charge; therefore, a conductor is not necessary to produce an electromagnetic wave.

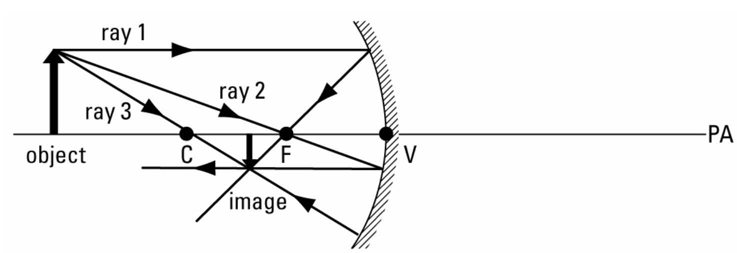
4. Hertz's experiment provided evidence that supported Maxwell's predictions about electromagnetic radiation. In this experiment, an induction coil rapidly changed the electric field across a spark gap (the radiator). When the electric field between the two electrodes forming the spark gap reached a sufficiently high value, the electrons "jumped" from one electrode to the other. As the charge was rapidly transferred, the electric field underwent a rapid change that caused a changing magnetic field, which then caused a changing electric field, and so on. An electromagnetic wave was produced and it radiated outward in all directions. When the changing electromagnetic field encountered the metal antenna, it induced a current flow, which was measured. The induced current flow in the antenna oscillated at a frequency identical to that of the changing electric field in the radiator. This was conclusive evidence that Hertz's device had indeed produced the electromagnetic radiation that was being observed at the antenna.

5. A changing magnetic field will produce a changing electric field (and vice versa). If the magnetic field lines held within a closed path are constant and unchanging, there will not be an electric field along the closed path. Similarly, if the electric field is constant and unchanging, it will not produce a magnetic field.

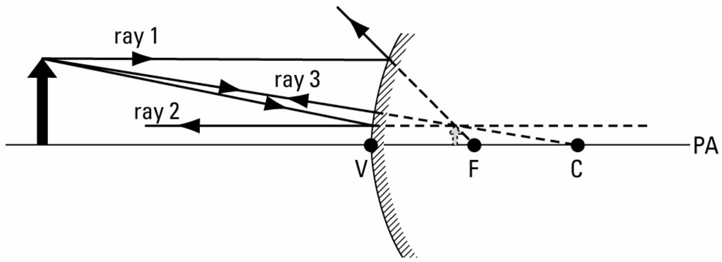
6. A spark produces EMR since there will be a rapidly changing electric field as the electrons accelerate from one electrode to another. The rapidly changing electric field induces a changing magnetic field, and so on, with both fields varying over time and travelling outward in all directions from the spark location.

7. The microwaves in a microwave oven consist of varying electric and magnetic fields. When they are incident on a metal conductor, such as a spoon, the varying electric field will induce current flow and charge separation in the conductor. The charge separation and current flow in the spoon can cause sparks to be produced.

8.



Converging mirror



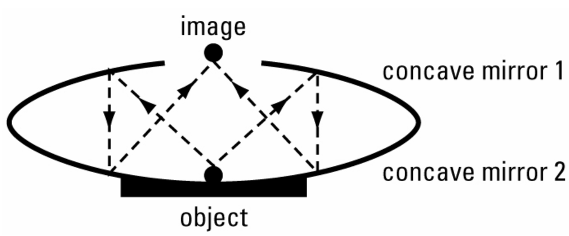
Diverging mirror

Incident Ray 1 is parallel to the principal axis. Any ray that is parallel to the principal axis will reflect through the focal point on a converging mirror, or appear to have originated from the focal point on a diverging mirror.
Incident Ray 2 travels through or from or toward the focal point. Any ray that passes through the focal point on a converging mirror, or is directed at the focal point on a diverging mirror, will be reflected back parallel to the principal axis.
Incident Ray 3 travels through or from or toward the centre of curvature. Any ray that passes through the centre of curvature on a converging mirror, or is directed at the centre of curvature on a diverging mirror, will be reflected directly back along the incident path.

9. The radius of curvature is twice as long as the focal length ($2f$) of the mirror.

10. A virtual focal point represents the position where several reflected rays appear to have converged or originated. For example, any ray that is directed at the virtual focal point on a diverging mirror will be reflected back parallel to the principal axis. And any ray that travels parallel to the principal axis will be reflected such that it appears to have originated or passed through from the virtual focal point.

11.



Two rays from the object are incident on concave mirror 1 and are reflected parallel to the principal axis. These two rays are reflected from concave mirror 2 and converge at the focal point. A small hole is cut in mirror 1 so that the real image forms above the top of mirror 1.

12. When you pull the concave side of a polished spoon away from your nose, your image disappears when the distance between the spoon and your nose is equal to the focal length of the reflector. At the focal length, the reflected rays travel outward, parallel to one another, never converging or appearing to have converged at any point. Therefore, no image is formed.

13. A paddle appears bent when you put it in water because of the visual effects created by refraction. As the light rays from the submerged section of the paddle exit the water and enter the air, they are refracted, changing the direction of travel and producing the visual effect of a “bent” object.

14. According to Snell's Law, the wavelength of EMR changes when it enters a new medium. Snell's Law supports the wave model of light, since it relates wavelength to the angles of incidence and refraction and to the velocity of the wave.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

15. When light passes from air (n = 1.00) into water (n = 1.33), Snell's law predicts that the wavelength decreases by a factor of 1.33 according to:

$$\frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

$$\frac{\lambda_1}{\lambda_2} = \frac{1.33}{1.00}$$

$$1.00\lambda_1 = 1.33\lambda_2$$

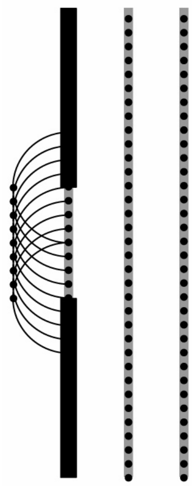
$$\lambda_1 = 1.33\lambda_2$$

16. As each person enters the water, his or her speed of travel is reduced compared to those who are still running on the land. The difference in speed between those in the water and those who are still travelling on land causes the line (or wave front) to change directions.

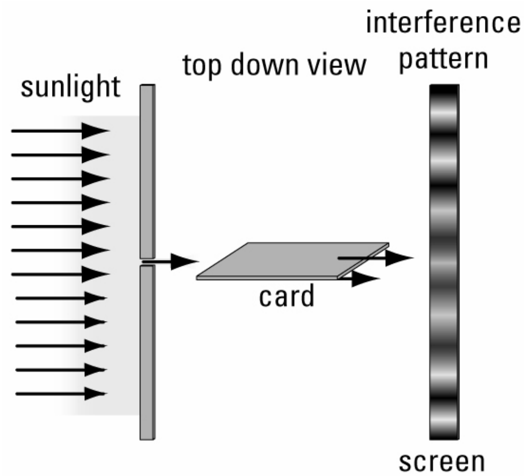
17. Newton set up two prisms. The first one was exposed to white light which produced a full spectrum of colours. The second prism was exposed only to red (monochromatic) light coming from the first prism. The second prism did not produce any more colours; only the red light emerged. As a second test, Newton inverted the second prism and allowed the spectrum of colours from the first prism to enter it. The spectrum disappeared and only white light emerged from the second prism. Based on these observations, Newton concluded that white light is made up of all the colours in the spectrum and the prism was separating –or dispersing–all the colours.

18. Huygens' Principle describes a wave front as consisting of many small point sources of tiny secondary waves, called wavelets, which propagate outward in a concentric circle at the same speed as the wave itself. The line tangent to all the wavelets constitutes the wave front.

19. As the secondary wavelets emerge from the opening, they form a new wave front, travelling outward with curved edges.



20. Young conducted his experiment using a pinhole in a window shutter and a card he described as "a slip of card, about one-thirtieth of an inch in breadth (thickness)." The card was positioned edgewise in the centre of a sunbeam such that it split the sunbeam into two coherent beams separated by a very small distance. Light coming from both sides of the card was in phase and the wave fronts created a fixed interference pattern of light and dark bands, called interference fringes, on a nearby screen.



21. Diffraction occurs when a wave front encounters a small opening or aperture in a barrier. When passing through the opening, the wave front changes both shape and direction according to Huygens' Principle, which describes EMR as a wave. In addition, the wavelets that constitute the wave front may also interfere, a process which can only be explained by assuming EMR has wave properties.

22. In 1818, Dominique Arago experimentally verified "Poissson's Bright Spot", providing strong evidence for the wave model of light. Poissson's bright spot is explained by constructive interference occurring at the center of a shadow when monochromatic light diffracts around the edge of a small disc. The prediction of this pattern, based on wave interference, and the verification of the pattern was crucial to the acceptance of the wave model of light.

23. When unpolarized light is incident on a polarizing filter, only one plane of the electric field is allowed to pass through, causing plane polarized light to emerge. If a second polarizing filter is held at right angles to the plane polarized light, then the plane polarized light also is absorbed – fully blocking all of the electromagnetic radiation from passing through the filters.

24. Electromagnetic waves are defined by varying electric and magnetic fields travelling through space. The periodic variations in the transverse electric and magnetic fields occur at right angles to one another and to the direction of propagation. Therefore, an electromagnetic wave is three dimensional.

Chapter 14

25. No. The energy of a quantum of light (photon) is given by $E = nhf$, where n is the number of photons, h is Planck's constant, and f is frequency. A quantum of blue light has a higher frequency and therefore higher energy than a quantum of red light.

26. ***Given***

$\lambda = 550 \text{ nm}$

Required

photon energy (E)

Analysis and Solution

Use the equation $E = nhf$, where $n = 1$.

$$\begin{aligned} E &= hf \\ &= \frac{hc}{\lambda} \\ &= \frac{\left(6.63\times10^{-34}\ \text{J}\cdot\cancel{\text{s}}\right)\left(3.00\times10^{8}\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}\right)}{550\times10^{-9}\ \cancel{\text{m}}} \\ &= 3.62\times10^{-19}\ \text{J} \end{aligned}$$

Paraphrase

The energy of a 550-nm photon is $3.62\times10^{-19}\ \text{J}$.

27. Temperature affects the shape of the blackbody curve, and especially the colour at which maximum intensity of emission occurs. For example, a bluish-white-coloured star is hotter than a reddish-coloured star. If you compare the blackbody curve for incandescent objects of known temperatures with the blackbody curves produced by the spectra of stars, you can estimate the temperature of the star. This temperature is only approximate, however, because stars are not perfect blackbody radiators.

28. gamma ray photon, 10-nm photon, ultraviolet photon, 600-nm photon, infrared photon, microwave photon

29. ***Given***

$\lambda = 500 \text{ nm}$

Required

frequency (f)

Analysis and Solution

$$c = f\lambda$$

$$f = \frac{c}{\lambda}$$

$$f = \frac{3.00\times10^{8}\ \frac{\cancel{\text{m}}}{\text{s}}}{500\times10^{-9}\ \cancel{\text{m}}}$$
$$= 6.00\times10^{14}\ \text{Hz}$$

Paraphrase

The frequency of blue light of wavelength 500 nm is $6.00\times10^{14}\ \text{Hz}$.

30. Ultraviolet photons are energetic enough (have a high enough frequency, from the equation $E = hf$) to cause cell damage in the skin (sunburn), whereas visible light photons are not sufficiently energetic.

31. Threshold frequency is the minimum frequency of illumination that will cause photoemission to occur from a metal surface. Light below this frequency, regardless of its intensity, will not cause emission of electrons from the metal surface.

32. The energy of photoelectrons does not depend on the intensity of the incident light. The number of electrons emitted increases with increasing intensity, however.

33. ***Given***

$W_0 = 3.2$ eV

Required

minimum wavelength for photoemission (λ)

Analysis and Solution

Light that has a frequency equal to the threshold frequency will just cause photoemission. The kinetic energy of the emitted electrons will be zero.
Convert 3.2 eV into joules and use the equation

$$E_\text{k} = hf - W_0$$
$$0 = hf_0 - W_0$$
$$hf_0 = W_0$$
$$f_0 = \frac{W_0}{h}$$
$$\lambda = \frac{c}{f}$$
$$= \frac{c}{\frac{W_0}{h}}$$
$$= \frac{ch}{W_0}$$
$$\lambda = \frac{\left(3.00\times10^{8}\ \frac{\text{m}}{\cancel{\text{s}}}\right)\left(6.63\times10^{-34}\ \cancel{\text{J}}\cdot\cancel{\text{s}}\right)}{\left(3.2\ \cancel{\text{eV}}\right)\left(1.60\times10^{-19}\ \frac{\cancel{\text{J}}}{\cancel{\text{eV}}}\right)}$$
$$= 3.88\times10^{-7}\ \text{m}$$

Paraphrase

The minimum wavelength of light that will cause photoemission is 388 nm.

34. The Compton effect is the elastic scattering of photons from matter—often X rays scattering off electrons or other small, subatomic particles. The photoelectric effect is the absorption of the energy of a photon, which leads to the emission of an electron from a metal surface. Even though they are distinct phenomena, they both exhibit the particle nature of light.

35. The term "wave–particle duality" refers to the unusual situation that both matter and energy, under appropriate conditions, exhibit either wave-like or particle-like properties. Waves and particles are opposing concepts, and this dual nature of light is referred to as the wave–particle duality.

36. ***Given***

$\lambda = 300 \text{ nm}$

Required

photon momentum (p)

Analysis and Solution

De Broglie's relation also applies to photons, so use the equation $p = \frac{h}{\lambda}$.

$$p = \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{300 \times 10^{-9} \text{ m}}$$
$$= 2.21 \times 10^{-27} \text{ N} \cdot \text{s}$$

Paraphrase

The momentum of the 300-nm photon is 2.21×10^{-27} N·s.

37. ***Given***

$v_e = 3000$ km/s

Required

de Broglie wavelength (λ)

Analysis and Solution

$$p = \frac{h}{\lambda}$$
$$\lambda = \frac{h}{p}$$
$$= \frac{h}{mv}$$
$$\lambda = \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{\left(9.11 \times 10^{-31} \text{ kg}\right)\left(3.000 \times 10^{6} \text{ m/s}\right)}$$
$$= 2.43 \times 10^{-10} \text{ m}$$

Paraphrase

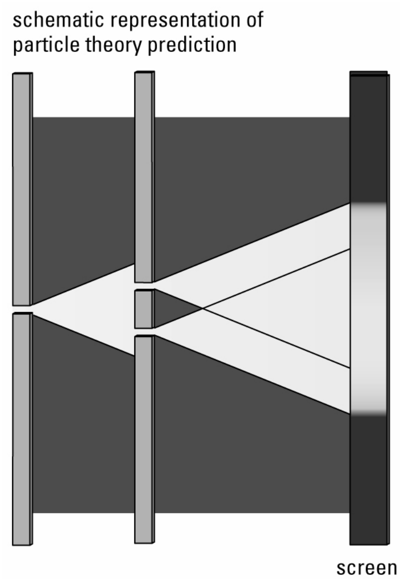
The electron has a de Broglie wavelength of 0.243 nm.

38. The de Broglie wavelength is inversely related to momentum. The neutron is slightly more massive than the proton, so the neutron has greater momentum, and hence a smaller de Broglie wavelength, than the proton.

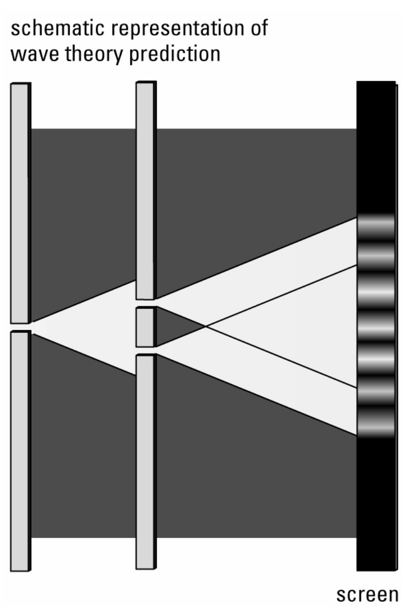
39. If a particle is confined to a fixed region in space, then the uncertainty in its position is, at most, equal to the size of the region in which the particle is located. According to Heisenberg's uncertainty principle, the smaller the uncertainty in position, the greater is the uncertainty in momentum of the particle. So, if you know roughly were the particle is, there must also be an uncertainty in its momentum. This means that the particle cannot have zero momentum. Because momentum and energy are related by the equation $E_k = \frac{p^2}{2m}$, the particle cannot be at rest and hence must have some energy.

Applications

40. If visible light (incident on two small holes) is a particle, we would expect to observe a large bright region where the light from each slit overlaps. Or, if the holes were sufficiently far apart, you would observe two bright regions, one for each opening.



What is actually observed when light passes through two small holes is an interference pattern. This pattern supports the wave model of light since only waves would be expected to show the constructive and destructive interference required to produce the observed pattern.



41. ***Given***

$f = 90.9$ MHz

$P = 50$ kW

Required

the number of photons per second (n)

Analysis and Solution

Use the equations $E = nhf$ and $P = \frac{E}{\Delta t}$. The radio station emits 50 kW or 50 kJ/s, so $E = 50$ kJ. Rearrange Planck's equation to solve for the number of photons.

$$\begin{aligned} n &= \frac{E}{hf} \\ &= \frac{50 \text{ kJ}}{(6.63 \times 10^{-34} \text{ J} \cdot \text{s})(90.9 \text{ MHz})} \\ &= \frac{50\ 000 \ \cancel{\text{J}}}{(6.63 \times 10^{-34} \ \cancel{\text{J}} \cdot \cancel{\text{s}})(90.9 \times 10^{6} \ \cancel{\text{Hz}})} \\ &= 8.3 \times 10^{29} \end{aligned}$$

Paraphrase

The radio station emits 8.3×10^{29} radio photons each second.

42. An antenna is a conductor which is able to "sense" electromagnetic radiation by tuning into the induced current flow in the antenna. The rate of change of the induced current in the antenna corresponds to the frequency of the varying electric field in the electromagnetic wave.

43. ***Given***

$\Delta t = 2.56$ s

$c = 3.00 \times 10^{8}$ m/s

Required

distance (Δd)

Analysis and Solution

The distance from the surface of Earth to the surface of the moon is equal to one half the round trip distance that the light travels in 2.56 s at the speed of light in a vacuum (c).

$$\begin{aligned} c &= \frac{\Delta d}{\Delta t} \\ \Delta d &= c\Delta t \\ \Delta d_{\text{roundtrip}} &= c\Delta t \\ \Delta d_{\text{roundtrip}} &= (3.00 \times 10^{8} \text{ m/s})(2.56 \text{ s}) \\ \Delta d_{\text{roundtrip}} &= 7.68 \times 10^{8} \text{ m} \\ \Delta d_{\text{oneway}} &= \frac{7.68 \times 10^{8} \text{ m}}{2} \\ \Delta d_{\text{oneway}} &= 3.84 \times 10^{8} \text{ m} \\ \Delta d_{\text{oneway}} &= 3.84 \times 10^{5} \text{ km} \end{aligned}$$

Paraphrase

The surface of the moon is 3.84×10^5 km from the surface of Earth.

44. No, increasing the intensity of the light does not change the energy of each photon. You can only change the energy of the photons by changing the frequency of the photons. Increasing the intensity increases the *number* of photons.

45. ***Given***

$$\frac{1 \text{ rotation}}{16 \text{ sides}}$$

$$v = 2.97 \times 10^8 \text{ m/s}$$

$$f = \frac{1.15 \times 10^4 \text{ rot}}{60 \text{ s}} = 191.6666667 \text{ Hz}$$

Required

distance (d)

Analysis and Solution

Unit analysis can be used to determine the distance that the light can travel during 1/16th of a rotation. The given information must be arranged as follows

$$d = \frac{\cancel{\text{rot}}}{\text{side}} \times \frac{\text{m}}{\cancel{\text{s}}} \times \frac{\cancel{\text{s}}}{\cancel{\text{rot}}}$$

$$d_{\text{total}} = \frac{1 \text{ rot}}{16 \text{ side}} \times \frac{2.97 \times 10^8 \text{m}}{1 \cancel{\text{s}}} \times \frac{1 \cancel{\text{s}}}{191.6666667 \text{ rot}}$$

$$d_{\text{total}} = 96847.82607 \text{ m}$$

$$d = \frac{96847.82607 \text{ m}}{2} = 4.84 \times 10^4 \text{ m}$$

Paraphrase

The fixed mirror should be place 4.84×10^4 m from the 16-sided rotating mirror.

46. ***Given***

$$\frac{1 \text{ rotation}}{8 \text{ sides}}$$

$$c = 3.00 \times 10^8 \text{ m/s}$$

$$d = (5.00 \times 10^3 \text{ m})(2) = 1.00 \times 10^4 \text{ m}$$

Required

frequency of rotation (rot/s = Hz)

Analysis and Solution

Unit analysis can be used to determine the frequency of rotation in Hertz. The given information must be arranged as follows

$$f = \frac{\text{rot}}{\text{side}} \times \frac{\cancel{\text{m}}}{\text{s}} \times \frac{1}{\cancel{\text{m}}} = \frac{\text{rot}}{\text{s}} = \text{Hz}$$

Solution

$$f = \frac{1 \text{ rot}}{8 \text{ side}} \times \frac{3.00 \times 10^8 \cancel{\text{m}}}{1 \text{ s}} \times \frac{1}{1.00 \times 10^4 \cancel{\text{m}}}$$

$$f = 3750 \frac{\text{rot}}{\text{s}}$$

$$f = 3.75 \times 10^3 \text{ Hz}$$

Paraphrase

The 8-sided mirror was rotating at a frequency of 3.75×10^3 Hz.

47. ***Given***

A sixteen-sided mirror

$$\frac{1 \text{ rotation}}{16 \text{ sides}}$$

$$f = 4.50 \times 10^2 \text{ Hz} = 4.50 \times 10^2 \frac{\text{rot}}{\text{s}}$$

Required

time to make one sixteenth of a rotation (t)

Analysis and Solution

Unit analysis can be used to determine the time. The given information must be arranged as follows:

$$t = \frac{\text{rot}}{\text{side}} \times \frac{\text{s}}{\text{rot}} = \frac{\text{s}}{\text{side}}$$

$$t = \frac{1 \text{ rot}}{16 \text{ side}} \times \frac{1 \text{ s}}{4.50 \times 10^2 \text{ rot}}$$

$$t = 1.39 \times 10^{-4} \frac{\text{s}}{\text{side}}$$

Paraphrase

The 16-sided rotating mirror takes 1.39×10^{-4} s to make 1/16th of a rotation.

48. At night, visible light is not intense enough for police search and rescue personnel to see people. Since human bodies release infrared radiation which has an intensity greater than that of the background, they can be sensed by observing the infrared radiation, which emanates from all warm objects, such as people and animals.

49. ***Given***

$v_{\text{material}} = 1.24 \times 10^8$ m/s

$c_{\text{in air}} = 3.00 \times 10^8$ m/s

Required

The refractive index of the unknown material (n)

Analysis and Solution

The index of refraction is a ratio of the speed of light in the medium to the speed of light in a vacuum. The index will be used to identify the unknown material.

$$n = \frac{c}{v}$$

$$n_{\text{unknown}} = \frac{c}{v} = \frac{3.00 \times 10^8 \text{ m/s}}{1.24 \times 10^8 \text{ m/s}}$$

$$n_{\text{unknown}} = 2.42$$

Paraphrase and Verify

The refractive index of the unknown material is 2.42, which is equal to the refractive index of diamond. Therefore, the unknown material is diamond.

50. ***Given***

$\lambda = 520$ nm

$W_0 = 2.3$ eV

Required

to determine whether the metal surface will emit electrons

Analysis and Solution
Calculate the threshold frequency for the metal and the frequency of a 520-nm photon. Photoemission will occur if the frequency of the 520-nm photon is greater than the threshold frequency. Convert the work function units from electron volts into joules. Use the equations

$$hf_0 = W_0$$

$$f_0 = \frac{W_0}{h}$$

and

$$f = \frac{c}{\lambda}$$

For threshold frequency,

$$f_0 = \frac{(2.3\ \cancel{\text{eV}})\left(1.60 \times 10^{-19}\ \frac{\cancel{\text{J}}}{\cancel{\text{eV}}}\right)}{6.63 \times 10^{-34}\ \cancel{\text{J}} \cdot \text{s}}$$

$$= 5.55 \times 10^{14}\ \text{Hz}$$

The frequency of the 520-nm photon is

$$f = \frac{3.00 \times 10^{8}\ \frac{\cancel{\text{m}}}{\text{s}}}{520 \times 10^{-9}\ \cancel{\text{m}}}$$

$$= 5.77 \times 10^{14}\ \text{Hz}$$

The photon's frequency is greater than the threshold frequency.
Paraphrase
The metal surface will emit electrons when illuminated by 520-nm light.

51. ***Given***
An eight-sided mirror

$$\frac{1\ \text{rot}}{8\ \text{side}}$$

$f = 5.20 \times 10^{2}$ Hz

$d = 3.50 \times 10^{4}\ \text{m} \times 2 = 7.00 \times 10^{4}\ \text{m}$

Required
speed of light (c)
percent error
Analysis and Solution
The light travels the given, round-trip distance in the time it takes the rotating mirror to make one eighth of a rotation.

$$T = \frac{1}{f} \quad c = \frac{\Delta d}{\Delta t}$$

$$T = \frac{1}{5.20 \times 10^{2}\ \text{Hz}} = 1.9230769 \times 10^{-3}\text{s}$$

$$\Delta t = \frac{1}{8}T$$

$$\Delta t = \frac{1}{8}\left(1.9230769 \times 10^{-3}\text{s}\right)$$

$$\Delta t = 2.403846154 \times 10^{-4}\text{s}$$

$$c = \frac{7.00 \times 10^{4}\ \text{m}}{2.403846154 \times 10^{-4}\text{s}}$$

$$c = 2.91 \times 10^{8}\text{m/s}$$

$$\%\ error = \left|\frac{(\text{experimental value} - \text{accepted value})}{\text{accepted value}}\right| \times 100$$

$$\%\ error = \left|\frac{(2.91 \times 10^{8}\text{m/s} - 3.00 \times 10^{8}\text{m/s})}{3.00 \times 10^{8}\text{m/s}}\right| \times 100$$

$$\%\ error = 3.00\%$$

Paraphrase

The experimentally determined speed of light is 2.91×10^{8} m/s. This differs by 3% from the currently accepted value for the speed of light in air.

52. Above Earth's atmosphere, the aluminium will be illuminated by the strong UV rays and soft X rays emitted by the Sun. These frequencies will be well above the threshold frequency for aluminium. As a result, the aluminium metal will emit photoelectrons. Since the aluminium is losing electrons, it will become positively charged.

53. ***Given***

$f = -5.0$ cm

$d_i = -3.0$ cm

$h_i = 1.0$ cm

Required

object distance (d_o)

object height and attitude

Analysis and Solution

The object position can be found using the mirror equation as follows:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

$$\frac{1}{d_o} = \frac{1}{f} - \frac{1}{d_i}$$

$$\frac{1}{d_o} = \frac{1}{-5.0\ \text{cm}} - \frac{1}{-3.0\ \text{cm}}$$

$$d_o = +7.5\ \text{cm}$$

The object height and attitude can be found using the ratio of the image and object height to the image and object distance. The object attitude is determined by the sign of the object height. The relative size of the object is determined by comparing the image and object heights.

$$\frac{h_i}{h_o} = \frac{-d_i}{d_o}$$

$$h_o = \frac{h_i d_o}{-d_i}$$

$$h_o = \frac{(1.0cm)(+7.5cm)}{-(-3.0cm)}$$

$$h_o = +2.5cm$$

Paraphrase and Verify

The object is located 7.5 cm from the mirror. It is erect (indicated by the positive object height), and 2.5 cm high (larger than the virtual image).

54. Use the following expressions:

$$E = hf = h\frac{c}{\lambda} \text{ and } p = \frac{h}{\lambda}$$

Photon A has four times more energy than photon B, so it must have four times the frequency and hence one-quarter of the wavelength. Set up the following ratios:

$$\begin{aligned}\frac{E_A}{E_B} &= \frac{\cancel{h}\frac{\cancel{c}}{\lambda_A}}{\cancel{h}\frac{\cancel{c}}{\lambda_B}}\\ &= \frac{\lambda_B}{\lambda_A}\\ &= 4\\ \lambda_B &= 4\lambda_A\end{aligned}$$

and

$$\begin{aligned}\frac{p_A}{p_B} &= \frac{\frac{\cancel{h}}{\lambda_A}}{\frac{\cancel{h}}{\lambda_B}}\\ &= \frac{\lambda_B}{\lambda_A}\\ &= 4\\ p_A &= 4p_B\end{aligned}$$

So, it follows that photon A has four times the momentum of photon B.

55. ***Given***

$\theta_1 = 10°$

From Table 13.4:

$n_1 = 1.33$

$n_2 = 1.54$

Required

angle of refraction (θ_2)

Analysis and Solution

The angle of refraction is calculated using Snell's Law.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

$$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right)$$

$$\theta_2 = \sin^{-1}\left(\frac{(1.33)(\sin 10°)}{1.54}\right)$$

$$\theta_2 = 8.6°$$

Paraphrase

The angle of refraction is 8.6°.

56. ***Given***

λ_{i} = 0.025 nm

$\theta = 90°$

m_{e} = 9.11 × 10^{-31} kg

Required

the change in energy of the electron and photon (ΔE)

Analysis and Solution

The X ray will lose some energy to the electron. Use the Compton equation to predict the change in wavelength of the X ray.

$$\Delta\lambda = \lambda_{\text{f}} - \lambda_{\text{i}} = \frac{h}{mc}(1 - \cos\theta)$$

$$\begin{aligned}\lambda_{\text{f}} &= \lambda_{\text{i}} + \frac{h}{mc}(1 - \cos\theta) \\ &= 0.025 \times 10^{-9}\ \text{m} + \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{\left(9.11 \times 10^{-31}\ \text{kg}\right)\left(3.00 \times 10^{8}\ \text{m/s}\right)}(1 - \cos 90°) \\ &= 2.74 \times 10^{-11}\ \text{m}\end{aligned}$$

From this change, determine the energy change.

$$\Delta E = h(f_{\text{f}} - f_{\text{i}}) = hc\left(\frac{1}{\lambda_{\text{f}}} - \frac{1}{\lambda_{\text{i}}}\right)$$

$$\begin{aligned}\Delta E &= hc\left(\frac{1}{\lambda_{\text{f}}} - \frac{1}{\lambda_{\text{i}}}\right) \\ &= \left(6.63 \times 10^{-34}\ \text{J} \cdot \text{s}\right)\left(3.00 \times 10^{8}\ \frac{\text{m}}{\text{s}}\right)\left(\frac{1}{2.74 \times 10^{-11}\ \text{m}} - \frac{1}{2.5 \times 10^{-11}\ \text{m}}\right) \\ &= -7.0 \times 10^{-16}\ \text{J}\end{aligned}$$

According to the law of conservation of energy, this energy, lost by the X ray, is gained by the electron.

Paraphrase

During the scattering event, the X-ray photon's wavelength increased to 0.027 nm. The electron gained 7.0 × 10^{-16} J of energy.

57. ***Given***

h_{o} = 3.0 cm

d_{o} = 10.0 cm

f = 5.0 cm

Required
image distance (d_i)
image height (h_i)
image attributes (location, type, attitude, and magnification)
Analysis and Solution
The image distance and height can be calculated by using the thin lens and magnification equations. The image attributes can be determined based on the sign and/or magnitude of the image distance and height.

$$\frac{1}{d_o}+\frac{1}{d_i}=\frac{1}{f}$$

$$\frac{1}{d_i}=\frac{1}{f}-\frac{1}{d_o}$$

$$\frac{1}{d_i}=\frac{1}{5.0\text{ cm}}-\frac{1}{10.0\text{ cm}}$$

$$d_i=10\text{ cm}$$

$$m=\frac{h_i}{h_o}=\frac{-d_i}{d_o}$$

$$h_i=\frac{-d_i h_o}{d_o}$$

$$h_i=\frac{-(10\text{cm})(3.0\text{ cm})}{10.0\text{ cm}}$$

$$h_i=-3.0\text{ cm}$$

Paraphrase and Verify
The image forms 10 cm from the lens with a height of –3.0 cm. The image is real (indicated by the positive image distance), inverted (indicated by the negative height), and the same size as the object (indicated by comparing the height of the image and object).

58. (a) The underlying principle of this form of propulsion is the Compton effect, that is, that photons have momentum.

(b) ***Given***
P = 1 kW
λ = 500 nm
m = 1000 kg
Required
speed of spacecraft after one year (v_f)
Analysis and Solution
Use the energy output of the laser and the energy of each 500-nm photon to determine how many 500-nm photons are emitted by the laser drive each second.

$$P=\frac{\Delta E}{1\text{ s}}=\frac{nh\frac{c}{\lambda}}{1\text{ s}}=1000\text{ J/s}$$

$$n=\frac{\Delta E\lambda}{hc}$$

$$n = \frac{(1000\ \cancel{\text{J}})(500 \times 10^{-9}\ \cancel{\text{m}})}{(6.63 \times 10^{-34}\ \cancel{\text{J}} \cdot \cancel{\text{s}})\left(3.00 \times 10^{8}\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}\right)}$$
$$= 2.51 \times 10^{21}$$

The total momentum carried by all the photons each second is

$$p = n\left(\frac{h}{\lambda}\right)$$
$$= \left(2.51 \times 10^{21}\right)\left(\frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{500 \times 10^{-9}\ \text{m}}\right)$$
$$= 3.33 \times 10^{-6}\ \text{N} \cdot \text{s}$$

According to the law of conservation of momentum, the spacecraft must acquire an equal and opposite momentum each second. Use the basic expressions $F = \frac{\Delta p}{\Delta t}$ and $v_\text{f} = v_\text{i} + a\Delta t$, where Δt = 1 year = 3.15 × 10^7 s. Since $F = \frac{\Delta p}{\Delta t}$, the force exerted by the photons as they carry momentum away from the rocket is 3.33 ×10^{-6} N. The magnitude of the rocket's acceleration is

$$a = \frac{F}{m}$$
$$= \frac{3.33 \times 10^{-6}\ \text{N}}{1000\ \text{kg}}$$
$$= 3.33 \times 10^{-9}\ \text{m/s}^2$$

The final speed of the rocket is

$$v_\text{f} = v_\text{i} + a\Delta t$$
$$= 0 + \left(3.33 \times 10^{-9}\ \frac{\text{m}}{\text{s}^{\cancel{2}}}\right)\left(3.15 \times 10^{7}\ \cancel{\text{s}}\right)$$
$$= 0.105\ \text{m/s}$$

Paraphrase

In principle, the propulsion system works, but it is not very efficient—it only achieves a speed of 10.5 cm/s after one year!

59. The visible spectrum can be recomposed by refraction in a prism or by mixing all the colours using a high speed rotating disc.

60. ***Given***

V = 75 kV

Required

electron wavelength (λ)

Analysis and Solution

Use the basic relation $\lambda = \frac{h}{p}$. The electrons acquire kinetic energy, according to the equation $E_\text{k} = \frac{p^2}{2m}$.

Therefore,

$$p = \sqrt{2mE_k}$$
$$= \sqrt{2mqV}$$

Substitute this equation for momentum into the wave equation:

$$\lambda = \frac{h}{\sqrt{2mqV}}$$

$$\lambda = \frac{6.63\times10^{-34}\ \text{J}\cdot\text{s}}{\sqrt{2\left(9.11\times10^{-31}\ \text{kg}\right)\left(1.60\times10^{-19}\ \text{C}\right)\left(75\times10^{3}\ \text{V}\right)}}$$
$$= 4.48\times10^{-12}\ \text{m}$$
$$= 4.5\times10^{-12}\ \text{m}$$

Paraphrase

The wavelength of the electrons in the electron microscope is only 0.0045 nm, which is much smaller than the wavelength of light used in a conventional microscope.

61. If two waves arrive at the screen one half wavelength out of phase, then destructive interference will occur in this region. A region of destructive interference is observed as a dark fringe (or node) on the screen.

62. ***Given***

L = 1.0 nm

Required

the rest energy of the electron (E_k)

Analysis and Solution

For the electron to be contained in the box, its wavelength must be that of a standing wave. For minimum energy, the wavelength of the electron must be equal to twice the length of the box, or 2 nm. Use the equations $p = \frac{h}{\lambda}$ and $E_k = \frac{p^2}{2m}$.

$$p = \frac{6.63\times10^{-34}\ \text{J}\cdot\text{s}}{2.0\times10^{-9}\ \text{m}}$$
$$= 3.3\times10^{-25}\ \text{N}\cdot\text{s}$$

Use this value for momentum to calculate rest energy.

$$E_k = \frac{\left(3.3\times10^{-25}\ \text{N}\cdot\text{s}\right)^2}{2\left(9.11\times10^{-31}\ \text{kg}\right)}$$
$$= 6.0\times10^{-20}\ \text{J}$$
$$= 0.38\ \text{eV}$$

Paraphrase

The rest or minimum energy of the electron confined to a 1.0-nm box is 0.38 eV.

63. ***Given***

$d = \frac{1\ \text{cm}}{1.00 \times 10^{4}\ \text{lines}} = 1.00 \times 10^{-4}\ \text{cm}$

$d = 1.00 \times 10^{-6}\ \text{m}$

$n = 1$

$\lambda_{\text{violet}} = 4.20 \times 10^{-7}\ \text{m}$

$\lambda_{\text{red}} = 6.50 \times 10^{-7}\ \text{m}$

Required

angle of diffraction (θ)

Analysis and Solution

The first antinode is a region of constructive interference, where the path difference must be one whole wavelength. Therefore, the generalization for the difference in path length for an antinode can be used to calculate the angle of diffraction for each wavelength.

$\lambda = \frac{d \sin\theta}{n}$

$\theta = \sin^{-1}\left(\frac{\lambda n}{d}\right)$

$\theta_{\text{violet}} = \sin^{-1}\left(\frac{(4.20 \times 10^{-7}\ \cancel{\text{m}})(1)}{1.00 \times 10^{-6}\ \cancel{\text{m}}}\right)$ $\theta_{\text{red}} = \sin^{-1}\left(\frac{(6.50 \times 10^{-7}\ \cancel{\text{m}})(1)}{1.00 \times 10^{-6}\ \cancel{\text{m}}}\right)$

$\theta_{\text{violet}} = 24.8°$ $\theta_{\text{red}} = 40.5°$

Paraphrase

The angle of diffraction to the first antinode for violet light is 24.8°; for red light it is 40.5°.

64. ***Given***

$d = \frac{1\ \text{cm}}{1.50 \times 10^{2}\ \text{slits}} = 6.6666667 \times 10^{-3}\ \text{cm}$

$d = 6.6666667 \times 10^{-5}\ \text{m}$

$\lambda = 7.00 \times 10^{-7}\ \text{m}$

$n = 1$

$L = 2.50\ \text{m}$

Required

the distance between adjacent antinodes (x)

Analysis and Solution

Taking the inverse of the lines/cm gives the slit separation (d). We assume that $n = 1$ and that the distance between the central antinode and the first bright fringe is the same as the distance between any two antinodes in the same interference pattern. The first bright region of constructive interference occurs when the path difference is one whole wavelength. Therefore, the generalization for the difference in path length for an antinode can be used to calculate the distance between any two antinodes (x).

$\lambda = \frac{xd}{nL}$

$x = \frac{\lambda n L}{d}$

$$x = \frac{(7.00 \times 10^{-7}\ \text{m})(1)(2.50\ \cancel{\text{m}})}{6.6666667 \times 10^{-5}\ \cancel{\text{m}}}$$

$$x = 2.63 \times 10^{-2}\ \text{m}$$

Paraphrase

Adjacent antinodes are separated by a distance of 2.62×10^{-2} m.

65. ***Given***

m = 2000 kg

v = 60 km/h

d = 222 m

Δt = 10 s

Required

the uncertainty in the teacher's speed (Δv)

Analysis and Solution

Use Heisenberg's uncertainty principle, $\Delta x \Delta p \geq \frac{h}{4\pi}$, to determine Δp, the uncertainty in momentum. You can estimate Δx by arguing that it cannot be greater than 222 m, the space over which the spotting plane saw the car.

$$\Delta p \geq \frac{h}{4\pi \Delta x}$$

$$\begin{aligned}\Delta p &\geq \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{4\pi(222\ \text{m})} \\ &\geq 2.38 \times 10^{-37}\ \text{N} \cdot \text{s}\end{aligned}$$

Use this answer for Δp to calculate Δv from the equation $\Delta p = m\Delta v$.

$$\begin{aligned}\Delta v &= \frac{\Delta p}{m} \\ &= \frac{2.38 \times 10^{-37}\ \text{N} \cdot \text{s}}{2000\ \text{kg}} \\ &\approx 10^{-40}\ \text{m/s}\end{aligned}$$

Paraphrase

Your physics teacher's excuse is pretty lame! Quantum effects cannot be invoked here. These effects are undetectable for a macroscopic object such as an automobile.

Extensions

66. The first layer is the unique digital identifier of the cell phone, used to verify the user, log activity, and locate the user relative to the cell tower infrastructure. The second layer is the digital stream of data which corresponds to the audio signals coming to and from the user's cell phone.

67. ***Given***

Δx = 0.20 nm

Required

the approximate momentum of an electron in a hydrogen atom (p)

the approximate energy of an electron in a hydrogen atom (E_k)

Analysis and Solution

Use Heisenberg's uncertainty principle, $\Delta x \Delta p \geq \frac{h}{4\pi}$, to estimate Δp.

$$\begin{aligned}\Delta p &\geq \frac{h}{4\pi\Delta x} \\ &\geq \frac{6.63\times10^{-34}\ \text{J}\cdot\text{s}}{4\pi(0.20\times10^{-9}\ \text{m})} \\ &\geq 2.6\times10^{-25}\ \text{N}\cdot\text{s}\end{aligned}$$

Then apply $E_\text{k} = \frac{p^2}{2m}$.

$$\begin{aligned}E_\text{k} &= \frac{\left(2.6\times10^{-25}\ \text{N}\cdot\text{s}\right)^2}{2\left(9.11\times10^{-31}\ \text{kg}\right)} \\ &= 3.8\times10^{-20}\ \text{J}\end{aligned}$$

Paraphrase

The energy of an electron confined to a hydrogen atom should be no less than 0.24 eV, with a momentum no less than $2.6\times10^{-25}\ \text{N}\cdot\text{s}$.

68. ***Given***

$\Delta d = 2.00\ \times\ 10^7\ \text{m}$

$c = 3.00\times10^8 \text{m/s}$

Required

time (Δt)

Analysis and Solution

The time it takes the signal to travel from the satellite to the receiver depends on the satellite's altitude and the speed at which the signal travels. All EMR is assumed to travel at the speed of light in air or in a vacuum.

$$c = \frac{\Delta d}{\Delta t}$$

$$\Delta t = \frac{\Delta d}{c} = \frac{2.00\ \times\ 10^7\ \cancel{\text{m}}}{3.00\times10^8 \cancel{\text{m}}/\text{s}}$$

$$\Delta t = 6.67\times10^{-2}\text{s}$$

Paraphrase

The signal travels from the satellite to the receiver in 6.67×10^{-2} s.

69. There are many problems with a large h value. You definitely would not want to go sunbathing! A 500-nm photon would carry a great deal of energy. If $h = 1\ \text{J}\cdot\text{s}$, then the energy of a single 500-nm photon would be

$$\begin{aligned}E &= hf \\ &= h\frac{c}{\lambda} \\ &= (1\ \text{J}\cdot\cancel{\text{s}})\frac{3.00\times10^8\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}}{500\times10^{-9}\ \cancel{\text{m}}} \\ &= 6\times10^{14}\ \text{J}\end{aligned}$$

This amount of energy is about the same as the energy released by 10 million kilograms of gasoline! If h = 1 J · s, then the de Broglie wavelength of a typical student moving at 1 m/s would be about

$$\begin{aligned}\lambda &= \frac{h}{p} \\ &= \frac{h}{mv} \\ &= \frac{1 \text{ J} \cdot \text{s}}{(50 \text{ kg})(1 \text{ m/s})} \\ &= 2 \text{ cm}\end{aligned}$$

Walking through a doorway could be dangerous because you may start to diffract! Recall from Chapter 13 that, when the size of an opening through which waves pass is comparable to the size of the waves themselves, diffraction effects become significant.

70. A fibre-optic tube transmits light using total internal reflection. The fibre itself is composed of a material with a high index of refraction (which has a relatively small critical angle). Light which is reflected through the fibre is always incident to the boundary at an angle larger than the critical angle. Therefore, none of the light is lost or absorbed outside of the fibre, ensuring that the signal intensity is preserved over long distances.

71. ***Given***

$P = 3.9 \times 10^{26}$ W

n = 10 000 photons/s

Required

the distance from which you could see the Sun (d)

Analysis and Solution

This problem needs to be solved in several steps.

1. First estimate how many visible light photons leave the surface of the Sun each second. To do this, estimate that half of the energy output of the Sun (2.0×10^{26} J/s) leaves as blue-green photons of average wavelength 500 nm.

   Use the equation $E = nhf = nh\frac{c}{\lambda}$ and solve for n.

   The number of blue-green photons leaving the Sun each second is approximately

$$\begin{aligned}E &= nhf = nh\frac{c}{\lambda} \\ n &= \frac{E\lambda}{hc} \\ &= \frac{\left(2.0 \times 10^{26} \cancel{\text{J}}\right)\left(500 \times 10^{-9} \cancel{\text{m}}\right)}{\left(6.63 \times 10^{-34} \cancel{\text{J}} \cdot \cancel{\text{s}}\right)\left(3.00 \times 10^{8} \frac{\cancel{\text{m}}}{\cancel{\text{s}}}\right)} \\ &= 5.0 \times 10^{44}\end{aligned}$$

2. Use the value for n to determine how many photons per square metre leave the surface of the Sun (the surface density of photons per square metre). Divide the number of photons leaving the Sun by the surface area of the Sun:

$\sigma_{\text{photons}} = \dfrac{n}{4\pi R^2}$, where σ_{photons} is the photon density.

$$\begin{aligned}\text{number of photons} &= 10\ 000 \\ &= A_{\text{eye}} \times \sigma_{\text{photons}} \\ &= \left(\pi r_{\text{pupil}}{}^2\right)\left(\frac{n}{4\pi R^2}\right)\end{aligned}$$

Solve for R (the Sun's radius).

$$R^2 = \left(\cancel{\pi} r_{\text{pupil}}{}^2\right)\left(\frac{n}{4\cancel{\pi}(10\ 000)}\right)$$

$$R = \sqrt{\left(r_{\text{pupil}}{}^2\right)\left(\frac{n}{4(10\ 000)}\right)}$$

3. Write an expression that shows how the surface density of photons per square metre changes as you move away from the Sun. As you move outward from the Sun, the density drops with the square of the distance.

   Use the equation $\sigma_{\text{photons}} = \dfrac{n}{4\pi R^2}$.

   Substitute $r_{\text{pupil}} = 3.5 \times 10^{-3}$ m and $n = 5.0 \times 10^{44}$ photons/s:

$$\begin{aligned}R &= \sqrt{\frac{\left(3.5\times10^{-3}\ \text{m}\right)^2\left(5.0\times10^{44}\right)}{40\ 000}} \\ &= 3.9\times10^{17}\ \text{m}\end{aligned}$$

4. Determine the distance from the Sun at which the total number of photons entering your eye is 10 000. One light year (the distance light travels in one year) is a more convenient unit to use. Since one light year equals 9.5×10^{15} m, the distance from which you can see the Sun is

$$\begin{aligned}d &= \frac{3.9\times10^{17}\ \cancel{\text{m}}}{9.5\times10^{15}\ \dfrac{\cancel{\text{m}}}{\text{ca}}} \\ &= 41\ \text{ca}\end{aligned}$$

Paraphrase and Verify

With a dark adapted eye, you should be able to see the Sun from a distance of about 41 light years. This estimate is actually very good: Simple astronomy using the distance modulus formula suggests that a person with very good vision under dark skies could see a star similar to our Sun from a distance of 52 ca (light years).

72. ***Given***

$E = 200$ eV

$d = 50$ nm

$L = 1$ m

Required

to predict what you will see when the electrons reach the phosphor screen

Analysis and Solution

This problem involves two-slit interference. Determine the wavelength of the electrons using the equation

$$\lambda = \frac{h}{p}$$
$$= \frac{h}{\sqrt{2mE_k}}$$

where E_k is the 200-eV energy of the electrons.
The de Broglie wavelength for the 200-eV electrons is

$$\lambda = \frac{h}{\sqrt{2mE_k}}$$
$$= \frac{6.63 \times 10^{-34}\ \cancel{\text{J}} \cdot \text{s}}{\sqrt{2\left(9.11 \times 10^{-31}\ \text{kg}\right)\left(200\ \cancel{\text{eV}}\right)\left(1.60 \times 10-19\ \frac{\cancel{\text{J}}}{\cancel{\text{eV}}}\right)}}$$
$$= 8.68 \times 10^{-11}\ \text{m}$$
$$= 0.0868\ \text{nm}$$

The two-slit interference formula is $n\lambda = d\sin\theta$, where n is the spectral order, d is the slit spacing, and θ is the angle at which antinodes form. You should expect to see a series of antinodes and nodes on the phosphor screen, which will appear as alternating bright and dark bands. The bright bands will be located at a distance given by the expression $\frac{x}{L} = \tan\theta$, where x is the distance of the bright bands on the phosphor screen and L is the 1-m separation between the screen and the two slits. Using the two-slit formula gives the following values for θ for the location of antinodes:

$$\sin\theta = \frac{n\lambda}{d}$$
$$= \frac{n\left(0.0868\ \cancel{\text{nm}}\right)}{50\ \cancel{\text{nm}}}$$
$$= n(0.00174)$$

The first three antinodes occur at angles of $0.099°$, $0.199°$, and $0.298°$, on either side of the central antinode, which is directly behind the midpoint of the two slits. The bright bands appear at locations given by $x = L\tan\theta$, where x = 0.0017, 0.0035, and 0.0052 m, on either side of the central maximum.

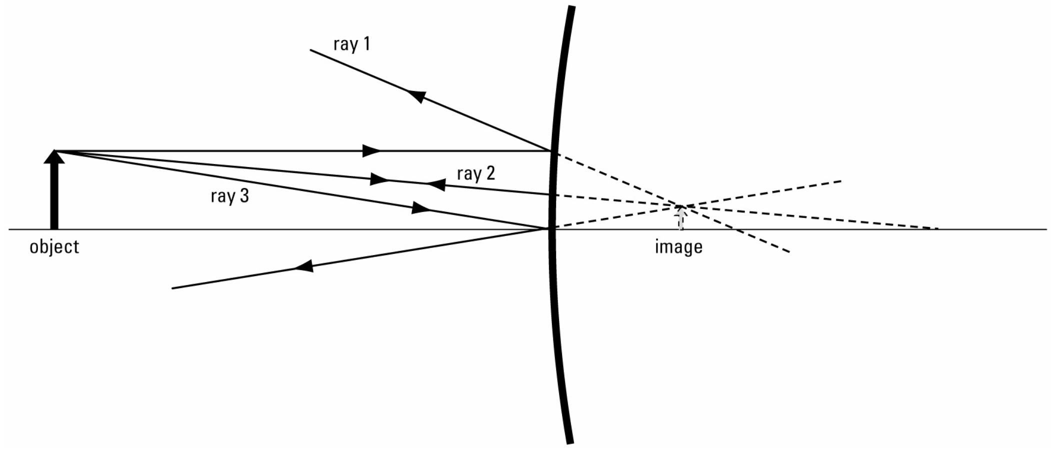
Paraphrase

A series of bright and dark lines will appear on the phosphor screen.

Skills Practice

73. ***Reasoning and Solution***

Incident Ray 1 is parallel to the principal axis. Any ray that is parallel to the principal axis will appear to have originated from the focal point on a diverging mirror.
Incident Ray 2 travels toward the centre of curvature. Any ray that is directed at the centre of curvature on a diverging mirror, will be reflected directly back along the incident path.
Incident Ray 3 travels towards the vertex. The vertex acts as a plane reflector, where the angle of incidence is equal to the angle of reflection.



Ray Diagram

The image is located approx. −7.0 cm from the mirror. It is virtual, erect, and magnified by approximately 0.25×.

Verification

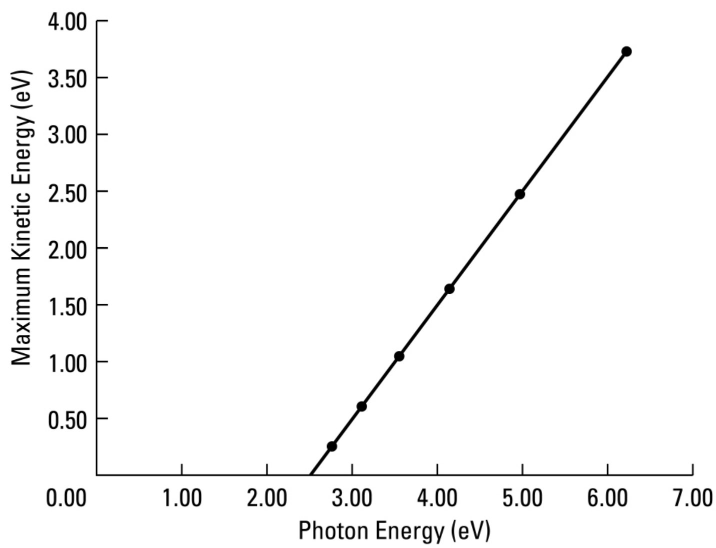
$$\begin{aligned}\frac{1}{d_\mathrm{i}} &= \frac{1}{f} - \frac{1}{d_\mathrm{o}} \\ &= \frac{1}{-10.0\ \text{cm}} - \frac{1}{25\ \text{cm}} \\ &= -0.1\ \text{cm} - 0.04\ \text{cm} \\ d_\mathrm{i} &= 7.14\ \text{cm}\end{aligned}$$

$$\begin{aligned}\mathrm{m} &= \frac{-d_\mathrm{i}}{d_\mathrm{o}} \\ &= \frac{-7.14\ \cancel{\text{cm}}}{25.0\ \cancel{\text{cm}}} \\ &= 0.286\times\end{aligned}$$

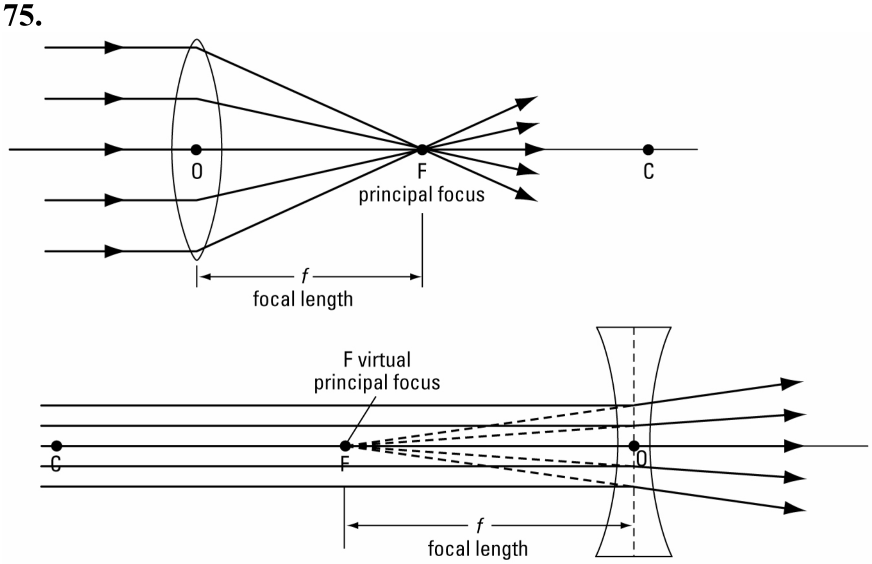
The image distance is 7.14 cm, and the magnification is 0.286×. The scale drawing gives a good approximation to the calculated values of image location and magnification.

74. Use the formula $E = hf = \dfrac{hc}{\lambda}$ to create a column of photon energies. Convert these energies into units of electron volts. Plot photon energy versus maximum kinetic energy and note where the *x*-intercept occurs. The *x*-intercept represents a photon energy that is just equal to the work function for the metal, $E_{\mathrm{k}_{\max}} = hf - W_0$, because $E_{\mathrm{k}_{\max}}$ is zero when the incident photon frequency equals the threshold frequency. By inspecting the graph, you can see that the work function, W_0, is 2.5 eV.

Wavelength (nm)	Energy of photons (eV)	Maximum Kinetic Energy (eV)
200	6.22	3.72
250	4.97	2.47
300	4.14	1.64
350	3.55	1.05
400	3.11	0.61
450	2.76	0.26



75.



A converging lens refracts all the rays that travel parallel to the principal axis through a common point, called the focal point. Therefore, the term “converging” is used to identify the lens. A diverging lens refracts all of the rays that travel parallel to the principal axis outwards; such that they will never converge at a real point in space. Therefore, the term "diverging" is used to identify the lens.

76. ***Given***

$E_k = 50$ keV

Required

the wavelength of the electron (λ)

the momentum of the electron (p)

Analysis and Solution

The mass of an electron is 9.11×10^{-31} kg . First calculate momentum using the equation

$$E_k = \frac{p^2}{2m}$$

$$p = \sqrt{2mE_k}$$

$$p = \sqrt{2\left(9.11 \times 10^{-31} \text{ kg}\right)\left(5.0 \times 10^{4} \text{ eV}\right)\left(1.60 \times 10^{-19} \text{ J/eV}\right)}$$

$$= 1.2 \times 10^{-22} \text{ kg} \cdot \text{m/s}$$

Use this answer to find wavelength using the equation

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

$$\lambda = \frac{6.63 \times 10^{-34} \text{ J} \cdot \text{s}}{1.2 \times 10^{-22} \text{ kg} \cdot \text{m/s}}$$

$$= 5.5 \times 10^{-12} \text{ m}$$

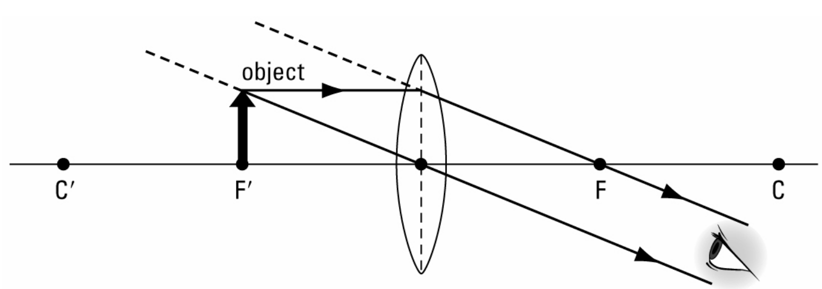
Paraphrase

The electron has a momentum of 1.2×10^{-22} kg·m/s and a wavelength of 5.5×10^{-12} m.

77. ***Reasoning and Solution***

Incident Ray 1 is parallel to the principal axis. Any ray that is parallel to the principal axis will be refracted through the focal point on a converging lens.

Incident Ray 2 travels towards the optical centre of the lens. Any ray that passes through the optical centre is laterally shifted, but not refracted.



When the object is located at the focal point of the lens, the refracted rays emerge parallel and never converge to form a real or virtual image.

78. ***Given***

$\lambda = 10$ nm

Required
momentum (p)
Analysis and Solution

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

$$\begin{aligned} p &= \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{10 \times 10^{-9}\ \text{m}} \\ &= 6.63 \times 10^{-26}\ \text{N} \cdot \text{s} \end{aligned}$$

Paraphrase
The X-ray photon has a momentum of $6.63 \times 10^{-26}\ \text{N} \cdot \text{s}$.

79.

Property of Light	**Best explained by…**
straight-line propagation	wave or particle model
reflection	wave or particle model
refraction	wave or particle model
polarization	wave model
dispersion	wave model
interference and diffraction	wave model
photoelectric effect, photoemission	particle model
Compton scattering	particle model

The best way to answer the question, “Is light a wave or a particle?” is to state that it is neither! The quantum world shows you that the behaviour of light depends on what property of light you are testing: Sometimes light exhibits wave properties and sometimes it exhibits particle properties.

Self-assessment

Students' answers in this section will vary greatly depending on their experiences, depth of understanding, and the depth of the research that they do into each of the topics.

