

ANSWERS

CHAPTER AN1

1.1 The de Broglie wavelength is given by

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

The rest energy of an electron is about 0.5 MeV and the electrons here have kinetic energies of 15 keV, so the non-relativistic approximation is OK - we can use the rest mass for m . So we need to find the speed. That can be found from the kinetic energy which can, in turn, be found from the potential difference V and the change in potential energy, eV .

$$\text{So the kinetic energy is } K = \frac{1}{2} m v^2 \text{ and } v = \sqrt{\frac{2K}{m}}$$

$$p = mv = m \sqrt{\frac{2K}{m}} = \sqrt{2mK} = \sqrt{2meV} \quad \text{since } K = eV$$

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

$$= \frac{6.63 \times 10^{-34} \text{ J.s}}{\sqrt{2 \times 9.11 \times 10^{-31} \text{ kg} \times 1.602 \times 10^{-19} \text{ C} \times 15 \times 10^3 \text{ V}}}$$

$$= 1.0 \times 10^{-11} \text{ m} = 0.010 \text{ nm}$$

This is much shorter than visible light wavelengths (about 500 nm). Wave effects would be noticed only on a scale much smaller than that at which we notice interference and diffraction effects for light. Wave effects would not be noticed in a TV tube.

1.2 Interference and diffraction effects become noticeable when the ratio of the wavelength λ to the a typical dimension d of the object becomes significant. As this ratio is often related to an angle, think about what is a noticeable angle. Let's pick 0.01 radian, about half a degree.

$$\text{a) } \lambda = \frac{h}{mv} \quad \text{so } \lambda = \frac{6.63 \times 10^{-34} \text{ J.s}}{1.0 \times 10^3 \text{ kg.m.s}^{-1}} = 7 \times 10^{-37} \text{ m and}$$

$$\frac{\lambda}{d} \approx 7 \times 10^{-37} \ll 0.01.$$

The wavelength is so small that wave effects are quite undetectable.

b) Spacing of fork prongs, $d \approx 2 \text{ mm}$. Wavelength of visible light $\lambda = 500 \text{ nm}$.

$$\frac{\lambda}{d} \approx \frac{500 \text{ nm}}{2 \text{ mm}} = 2 \times 10^{-4} < 0.01.$$

Interference and diffraction effects are difficult to detect.

c) As in question 1.1, calculate the wavelength from

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

$$= \frac{6.6 \times 10^{-34} \text{ J.s}}{\sqrt{2 \times 9.1 \times 10^{-31} \text{ kg} \times 10^4 \text{ eV} \times 1.6 \times 10^{-19} \text{ J.eV}^{-1}}}$$

$$\approx 1 \times 10^{-11} \text{ m.}$$

$$\text{So } \frac{\lambda}{d} \approx \frac{1 \times 10^{-11} \text{ m}}{1 \times 10^{-9} \text{ m}} = 0.01.$$

Wave effects are detectable if the angular resolution of the apparatus is good enough.

(d) $\lambda = 4 \times 10^{-10} \text{ m}$ and $\frac{\lambda}{d} \approx 0.4 > 0.01$ so wave effects should be noticeable.

1.3 As in Q1.1: $\lambda = \frac{h}{\sqrt{2mK}}$

$$= \frac{6.6 \times 10^{-34} \text{ J}\cdot\text{s}}{\sqrt{2 \times (1.675 \times 10^{-27} \text{ kg}) \times (0.025 \times 1.6 \times 10^{-19} \text{ J})}}$$

$$= 0.18 \text{ nm.}$$

1.4 a) The kinetic energy is given by $K = (\gamma - 1)E_0$. So, using values from the data table,

$$\gamma = \frac{K}{E_0} + 1 = \frac{100 \text{ keV}}{0.511 \text{ MeV}} + 1 = 1.20 \quad [\text{Save } 1.1957 \text{ in the calculator.}]$$

b) The speed v can be found from the value of γ .

Rearrange $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

to get $v = \left(\sqrt{1 - \frac{1}{\gamma^2}} \right) \cdot c = 0.548 c = 1.6 \times 10^8 \text{ m}\cdot\text{s}^{-1}$.

c) $m = \gamma m_0 = 1.09 \times 10^{-30} \text{ kg.}$

1.5 $K = (\gamma - 1)E_0$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{2.90^2}{3.00^2}}} = 15.25$$

$$K = 14.25E_0 = 14.25 \times 938.3 \text{ MeV} = 1.34 \text{ GeV.}$$

1.6 The mass is $m = \gamma m_0$.

The fractional increase in mass is $\frac{m - m_0}{m_0} = \gamma - 1$.

We also have kinetic energy $K = (\gamma - 1)E_0$, so

$$\frac{m - m_0}{m_0} = \frac{K}{E_0} = \frac{20 \text{ keV}}{0.511 \text{ MeV}} = 0.039.$$

So the percentage increase in mass is 4 %.

1.7 The energy difference is given by $(\Delta m)c^2$ so

$$\begin{aligned} K = (\Delta m)c^2 &= 1.8 \times 10^{-34} \text{ kg} \times (3.00 \times 10^8 \text{ m}\cdot\text{s}^{-1})^2 \\ &= 1.6 \times 10^{-17} \text{ J} \quad [1.620 \times 10^{-17} \text{ J}] \\ &\approx 100 \text{ eV.} \end{aligned}$$

Since the kinetic energy of the electron is much less than its rest energy, we can use the non-relativistic approximation for the kinetic energy, $K = \frac{1}{2}mv^2$, so

$$v = \sqrt{\frac{2K}{m}} = \sqrt{\frac{2 \times 1.620 \times 10^{-17} \text{ J}}{9.11 \times 10^{-31} \text{ kg}}} = 6.0 \times 10^6 \text{ m}\cdot\text{s}^{-1}.$$

Although this is fast it is still essentially non-relativistic, being only 2% of the speed of light.

1.8 The total rest energy of the electron and the positron is $2 \times 0.511 \text{ MeV}$ or 1.022 MeV . The photon must have at least this much energy, more if the electron and positron are to have enough kinetic energy to move apart and escape from each other before they annihilate each other.

1.9 i) The energy released must be at least as much as the sum of the rest energies, 1.022 MeV (see answer 1.8). This value converts to 1.6×10^{-13} J.

ii) The energy of the two photons is 1.022 MeV, 0.511 MeV each. The wavelength is found from $E = hf$ and $\lambda f = c$ so

$$\begin{aligned}\lambda &= \frac{hc}{E} = \frac{1.24 \text{ keV}\cdot\text{nm}}{0.511 \times 10^{-6} \text{ eV}} \\ &= 2.4 \text{ pm}.\end{aligned}$$

1.10 i) Violet and red (see chapter L1).

ii) From $E = hf$ and $\lambda f = c$ we can write $E = \frac{hc}{\lambda}$

$$\text{so } E_1 = \frac{hc}{\lambda_1} = \frac{1.24 \text{ keV}\cdot\text{nm}}{400 \text{ nm}} = 3 \text{ eV}$$

$$\text{and } E_2 = 2 \text{ eV}.$$

1.11 The total energy emitted by a source radiating with power P in time interval t is $E = Pt$. The energy carried by N photons is $N \frac{hc}{\lambda}$. These quantities must be equal so

$$N = \frac{Pt \lambda}{hc}.$$

The factor $\frac{Pt}{hc}$ is the same in each of the three cases, so evaluate it first.

$$\frac{Pt}{hc} = \frac{1.0 \times 10^{-3} \text{ J}\cdot\text{s}^{-1} \times 1.00 \text{ s}}{6.63 \times 10^{-34} \text{ J}\cdot\text{s} \times 3.00 \times 10^8 \text{ m}\cdot\text{s}^{-1}} = 5.028 \times 10^{21} \text{ m}^{-1}.$$

$$\text{i) } N = 5.028 \times 10^{21} \text{ m}^{-1} \times 589 \times 10^{-9} \text{ m} = 3.0 \times 10^{15}.$$

$$\text{ii) } N = 3.2 \times 10^{15}.$$

$$\text{iii) } N = 3.8 \times 10^{11}.$$

CHAPTER AN2

2.1 i) 1.9 eV.

ii) As we saw several times in the answers for chapter AN1, $E = \frac{hc}{\lambda}$

$$\begin{aligned}\text{so } \lambda &= \frac{hc}{E} = \frac{1.24 \text{ keV}\cdot\text{nm}}{1.9 \text{ eV}} \\ &= 0.65 \text{ }\mu\text{m}.\end{aligned}$$

i ii) This is at the red end of the visible spectrum.

2.2 The ground state energy is -13.6 eV so the photon energy is 12.1 eV. The calculation follows the scheme of Q1. $\lambda = 103 \text{ nm}$. This is in the ultraviolet.

2.3 The energy which ends up in the laser pulse is 0.2% of 4000 J or 8 J. The average power P is equal to the energy E delivered divided by the pulse duration t .

$$P = \frac{48 \text{ J}}{50 \times 10^{-9} \text{ s}} = 16 \times 10^7 \text{ W} \text{ (0.16 GW)}.$$

The irradiance is the power per cross-sectional area of the beam so

$$I = \frac{16 \times 10^7 \text{ W}}{2 \times 10^{-6} \text{ m}^2} = 8 \times 10^{13} \text{ W}\cdot\text{m}^{-2}.$$

Compare this with the irradiance of sunlight at the Earth's surface, about $1 \text{ kW}\cdot\text{m}^{-2}$!

2.4 The two spectral lines are due to two separate transitions, from levels E_1 and E_2 say, to a common ground state E_0 .

So the energies and wavelengths are given by

$$E_1 - E_0 = \frac{hc}{\lambda_1} \quad \text{and} \quad E_2 - E_0 = \frac{hc}{\lambda_2}$$

$$\text{So } E_1 - E_2 = hc \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

$$= hc \left(\frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \right)$$

$$= 1.24 \text{ keV}\cdot\text{nm} \frac{0.597 \text{ nm}}{(589 \text{ nm})^2}$$

$$= 0.213 \times 10^{-3} \text{ eV} = 0.213 \text{ meV.}$$

2.5 See §2-7. The lower state of the laser transition should not be a ground state - otherwise laser light could be absorbed faster than it is produced.

2.6 As before

$$\begin{aligned} \lambda &= \frac{hc}{E} \\ &= \frac{1.24 \text{ keV}\cdot\text{nm}}{3 \times 10^{-3} \text{ eV}} \\ &= 0.4 \text{ mm.} \end{aligned}$$

This radiation is in the region of the spectrum known as the far infrared.

CHAPTER AN3

3.1 a) 6 hours is equal to one half life so half the sample is left.

b) 2 days or 48 hours is equal to 8 half lives so the fraction left is $\left(\frac{1}{2}\right)^8 = \frac{1}{256} = 0.004$.

c) 20 hours is equal to 3.3 half lives so the fraction left is $\left(\frac{1}{2}\right)^{3.3} = 0.10$.

3.2 Assuming that the two samples of wood are chemically identical and that activities quoted relate only to carbon-14 then the specific activity of the ancient wood declines according to the law

$$A = A_0 \left(\frac{1}{2}\right)^{\frac{t}{\tau}}$$

Here τ is the half life and A_0 is the original value of the specific activity which is assumed to be equal to that of modern wood.

$$\log\left(\frac{A}{A_0}\right) = \frac{t}{\tau} \log\left(\frac{1}{2}\right) \text{ so}$$

$$t = \tau \frac{\log\left(\frac{A}{A_0}\right)}{\log(0.5)}$$

$$= 5.7 \times 10^3 \text{ y} \times \frac{\log\left(\frac{0.15 \text{ kBq}\cdot\text{kg}^{-1}}{0.237 \text{ kBq}\cdot\text{kg}^{-1}}\right)}{\log(0.5)}$$

$$t = 3.8 \times 10^3 \text{ y.}$$

Note that you can use logarithms to any base in this calculation - the answer will not be affected.

3.4 a) The half life is 50 days. After 150 days (3 half lives) the activity is reduced to

$$\left(\frac{1}{2}\right)^3 \times 4.0 \times 10^5 \text{ Bq, i.e. } 5.0 \times 10^4 \text{ Bq or } 5.0 \text{ kBq.}$$

b) The measured activity in the oil indicates the fraction of the iron that has worn off

$$\text{Mass of iron worn off} = \frac{200 \text{ Bq}}{5.0 \times 10^4 \text{ Bq}} \times 0.030 \text{ kg} = 0.12 \text{ g.}$$

3.5 The radius of the neutron star, considered as one huge nucleus, is given by

$$r \approx r_0 A^{1/3}$$

where A is the number of neutrons. A can be found from the mass M of the star and the mass m_n of a neutron: $M = Am_n$.

$$\begin{aligned} \text{So } r &\approx r_0 \left(\frac{M}{m_n}\right)^{1/3} \\ &= 1.3 \times 10^{-15} \text{ m} \left(\frac{2 \times 10^{30} \text{ kg}}{1.68 \times 10^{-27} \text{ kg}}\right)^{1/3} \\ &= 14 \text{ km.} \end{aligned}$$

This is another indication of the extremely high density of nuclear matter.

3.6 The activity of a specimen is equal to λN where N is the number of radioactive atoms left. The number of atoms in a mass m of pure radium-226 is equal to $\frac{m}{M}$ where M is the mass of one radium-226 atom, about 226 u.

The decay constant is related to half life τ by

$$\lambda = \frac{\ln(2)}{\tau}$$

So the activity of mass m of radium is

$$R = \frac{\ln(2)}{\tau} \times \frac{m}{M}$$

In this case with m being exactly 1 g we have

$$\begin{aligned} R &= \frac{\ln(2)}{1620 \times 365 \times 24 \times 60 \times 60 \text{ s}} \times \frac{1.00 \times 10^{-3} \text{ kg}}{226 \times (1.66 \times 10^{-27} \text{ kg})} \\ &= 3.6 \times 10^{10} \text{ s}^{-1} = 3.6 \times 10^{10} \text{ Bq.} \end{aligned}$$

This is a fair approximation to the value quoted in the data table, 3.7×10^{10} Bq.

3.7 It is important to distinguish between atomic masses and nuclear masses. Since atomic binding energies are negligible compared with nuclear binding energies we can find the masses of the nuclei by subtracting the masses of the atomic electrons from the atomic masses.

LHS	Mass of original ${}^{14}_6\text{C}$ nucleus:	14.003 242 u	$- 6 m_e$
RHS	Mass of ${}^{14}_7\text{N}$ nucleus:	14.003 074 u	$- 7 m_e$
	Mass of beta particle:		$+ m_e$
	Mass of antineutrino:	0	
	Total mass of decay products:	14.003 074 u	$- 6 m_e$
	Missing mass, Δm :	0.000 168 u	

The maximum possible value of the electron's kinetic energy is obtained by assuming that it takes all the energy released. This is given by

$$K = \Delta m c^2$$

Using the conversion: $u = 931.5 \text{ MeV}/c^2$ we get

$$\begin{aligned} K &= (0.000 168 \times (931.5 \text{ MeV}/c^2)) c^2 \\ &= 0.156 \text{ MeV.} \end{aligned}$$

3.8 The activity R_D of the daughter is related to the activity R_P of the parent by the equation:

$$R_D = \lambda_D N_D = R_P (1 - e^{-\lambda_D t}) .$$

We could find the activity of the parent from its half life, the mass number and the mass m of radium in the sample. This calculation has already been done (for a different mass) in Q3.6, and we already know the specific activity of radium from the conversion factor, curies to becquerels. Since the sample has mass $m' (= 1.00 \text{ g})$, the mass of radium is found in terms of atomic masses M . The best information about the atomic mass of radium-226 comes from its mass number, approximately 226 u, but for chlorine we use the data to find the mean atomic mass.

$$M(\text{Cl}) = 0.76 \times 34.968 \text{ u} + 0.24 \times 36.965 \text{ u} = 35.45 \text{ u} .$$

$$\frac{m}{m'} = \frac{M(\text{Ra})}{M(\text{RaCl}_2)} = \frac{226 \text{ u}}{(226 + 2 \times 35.45) \text{ u}} = 0.761 .$$

So $m = 0.761 \text{ g}$ and the activity of the radium is

$$R_P = 0.761 \times 3.7 \times 10^{10} \text{ Bq} .$$

Now evaluate the factor in brackets, using $\lambda_D = \frac{\ln(2)}{\tau}$.

$$R_D = 0.761 \times 3.7 \times 10^{10} \text{ Bq} \left(1 - e^{-\frac{\ln(2) 1.00 \text{ d}}{3.83 \text{ d}}} \right)$$

$$= 4.66 \text{ GBq} .$$

Since only 90% of the radon is removed the activity of the extracted gas is 4.2 GBq.

3.9 About half a kilometre.

CHAPTER AN4

4.1 For material A $\frac{N_A}{N_0} = e^{-\mu_A x} = 0.80$

and for B $\frac{N_B}{N_0} = e^{-\mu_B x} = e^{-\frac{\mu_A x}{2}}$

Since $-\mu_A x = \ln(0.80)$,

$$\frac{N_B}{N_0} = e^{\frac{\ln(0.80)}{2}} = 0.89$$

so 89 % of the photons get through.

4.2 a) $\mu = \mu_m \rho = (0.0065 \text{ m}^2 \cdot \text{kg}^{-1}) \times 2.7 \times 10^3 \text{ kg} \cdot \text{m}^{-3} = 17.6 \text{ m}^{-1}$.

b) $\frac{N}{N_0} = e^{-\mu x} = e^{-(17.6 \text{ m}^{-1}) \times (0.030 \text{ m})} = 0.59$.

So about 60 % of the original photons get through.

4.3 See §4-7.

4.4 See §4-3.

4.5 See figure 4.5.

4.6 The sum of the rest energies of the particles is 1.02 MeV, so we must have at least that much energy. The photon has to interact with something - it is not inherently unstable.

4.7 See figure 4.12.

- 4.8** a) Pair-production, because it has the largest attenuation coefficient.
 b) Adding the values gives $6.3 \times 10^{-3} \text{ m}^2 \cdot \text{kg}^{-1}$.
 c) See figure 4.12. μ_m (pe) decreases; μ_m (C) decreases; μ_m (pp) increases.

4.9 From the graph, the mass stopping power S is about $0.13 \text{ MeV} \cdot (\text{kg} \cdot \text{m}^2)^{-1}$.

We can rewrite $-\frac{1}{\rho} \frac{dE}{dx} = S$ in terms of small differences as

$$-\frac{1}{\rho} \frac{\Delta E}{\Delta x} = S$$

so $\Delta E = -S\rho \Delta x$

$$= -0.13 \text{ MeV} \cdot (\text{kg} \cdot \text{m}^2)^{-1} \times 11.4 \times 10^3 \text{ kg} \cdot \text{m}^{-3} \times 0.015 \text{ m}$$

$$= -2 \text{ MeV}.$$

4.10 The distance travelled = $\frac{\text{density thickness range}}{\text{density}}$

$$= \frac{1500 \text{ kg} \cdot \text{m}^{-2}}{1 \text{ kg} \cdot \text{m}^{-3}} = 1 \text{ km}.$$

In principle this is an overestimate because we used the stopping power at minimum ionisation.

4.11 Cherenkov radiation can just occur when the speed of the particle is just equal to the speed v of light in the medium, $\frac{c}{n}$, i.e. when $\frac{v}{c} = \frac{1}{n}$. The relativistic factor is

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

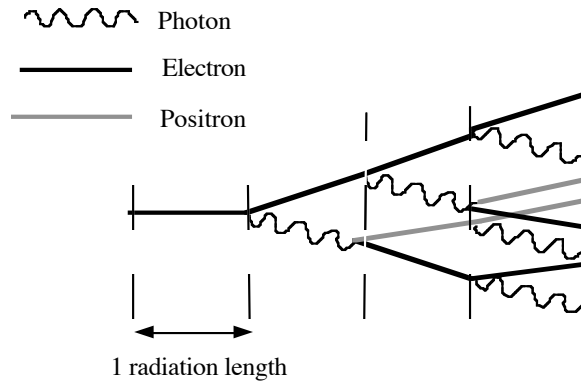
$$= \frac{1}{\sqrt{1 - \frac{1}{n^2}}}$$

For water $\gamma = 1.52$, for glass $\gamma = 1.32$ and for air $\gamma = 41$.

- 4.12** a) Compare what happens to an electron and a proton passing along the same track. The force exerted on each is about the same in magnitude, but since the electron is less massive it suffers a larger acceleration which produces more radiation and therefore more energy loss.
 b) When an electron penetrates an atom it experiences a force from the nucleus. This force depends on the nuclear charge, Ze . The higher the atomic number, the higher is the force and the radiation loss

- 4.13** The rest energy of an electron is about 0.5 MeV, so the ratios, kinetic energy to rest energy, are (a) 0.2, (b) 2, (c) 20 and (d) 200.
 (a), (b) collision loss
 (c), (d) radiation loss.

- 4.14** From table 4.1 the radiation length in lead is about 5.6 mm. So in 20 mm we get just under 4 radiation lengths. The diagram shows what can happen when the original electron has penetrated nearly 4 radiation lengths. We now have 3 electrons, 2 positrons, and 3 gamma ray photons - 8 particles altogether. The total number of particles increases roughly as 2^n where n is the number of complete radiation lengths travelled.



- 4.15** When a neutron collides with a light particle it can transfer a lot of kinetic energy, but when it strikes a heavy particle it transfers little energy - like a ball bouncing off a massive wall. See the discussion in the « » brackets in §4-10.

- 4.16** If collision losses dominate and the particles all have the same charge, the fastest particle will penetrate most because it spends less time near the atoms with which it interacts. The beta particle (electron) is fastest because it is the lightest, so it penetrates more than the proton. The proton is also more massive than an alpha particle so if the charges were the same it would penetrate more. But the alpha particle also has higher charge which causes it to lose energy even more rapidly than a singly charged particle of the same mass, so it penetrates even less.

- 4.17** The relativity principle says that nothing can go faster than c the speed that light goes in a vacuum. In a material with refractive index n light travels at a speed of c/n . Cerenkov radiation occurs when a charged particle travels through a material at a speed greater than c/n (but less than c).

- 4.18** Very fast particles lose energy mostly bremsstrahlung (see figure 4.19). As they slow down ionisation (and excitation) losses start to become more important. As the particles slow even more the dominant loss mechanism becomes ionisation loss and the stopping power for ionisation decreases with decreasing speed until it reaches a minimum. As the particles slow down even more the stopping power (still mainly ionisation and excitation loss) rises until the particles eventually come to rest.

CHAPTER AN5

5.1 We need a value of the mass stopping power. This can be estimated from figure 4.19 by making a few judicious assumptions. Since stopping power does not depend much on composition pick somewhere between the two curves shown. The ratio of kinetic energy to rest energy for a 1 MeV electron is about 2 so the particles produce roughly minimum ionisation. A value of $S = 0.2 \text{ MeV} \cdot (\text{kg} \cdot \text{m}^{-2})^{-1}$ should do.

Now proceeding as in Q4.9:

$$S = -\frac{1}{\rho} \frac{dE}{dx} = -\frac{1}{\rho} \frac{\Delta E}{\Delta x}$$

$$\text{so } \Delta E = -S\rho \Delta x.$$

This energy loss is related to the number n of ionising collisions, each of which produces an energy change of E' (35 eV) by

$$\Delta E = -nE'.$$

So for one particle going through, $S\rho \Delta x = nE'$ and

$$\begin{aligned} n &= \frac{S\rho \Delta x}{E'} \\ &= \frac{(0.2 \text{ MeV} \cdot (\text{kg} \cdot \text{m}^{-2})^{-1}) \times (1.3 \text{ kg} \cdot \text{m}^{-3}) \times 30 \text{ mm}}{35 \text{ eV}} \\ &= 2 \times 10^2 \quad [223] \end{aligned}$$

The total electron charge produced is equal to ne per particle:

$$\begin{aligned} Q &= ne \\ &= 223 \times 1.60 \times 10^{-19} \text{ C} \\ &= 4 \times 10^{-17} \text{ C} \quad [3.57 \times 10^{-17} \text{ C}]. \end{aligned}$$

For N ionising particles we get a charge separation. As these electrons move towards one electrode, positive ions carry an equal magnitude of charge the other way, so the average current is

$$I = \frac{2NQ}{t} = \frac{2 \times 100 \times 3.57 \times 10^{-17} \text{ C}}{1.0 \text{ s}} = 7 \times 10^{-15} \text{ A}.$$

That is a very tiny current, so you can see why some kind of amplification process is needed.

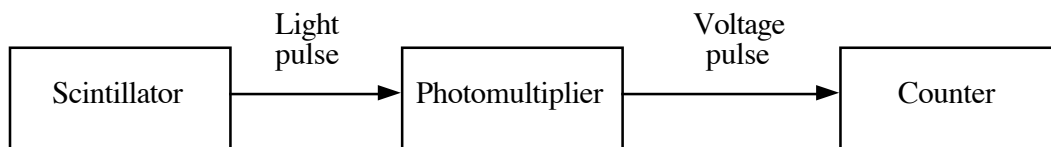
5.2 See §5-2.

5.3 The number N of photons that get through is given by

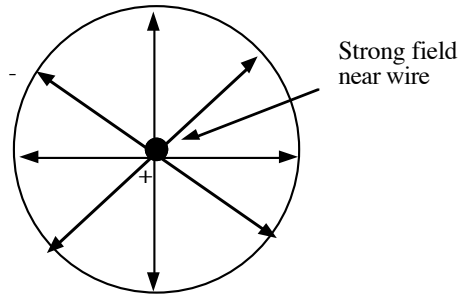
$$\begin{aligned} N &= N_0 e^{-\mu x} \\ &= 2000 e^{-0.01 \text{ m}^2 \cdot \text{kg}^{-1} \times 1.8 \text{ kg} \cdot \text{m}^{-3} \times 0.300 \text{ m}} \\ &= 1989 \end{aligned}$$

So about 10 photons are absorbed.

5.4



5.5 The central wire is positive.



Amplification takes place where the electric field is strong enough to accelerate electrons sufficiently between collisions so that they acquire enough energy to ionise the next atom they hit. The field is strongest near the central wire.

5.6 See §5-2.

5.7 See §5-2.

5.8 To produce an electrical signal (a charge) from a flash of light and to amplify the signal.

5.9 Positive ions and free electrons need to be mobile so that a current can be formed. In a denser material recombination may take place before the current can be established.

5.10 Charged particles will lose some energy and may even be stopped completely in the walls. Very thin walls are needed to let alpha particles in.

Gamma ray photons which interact within the walls may go undetected or they may produce secondary electrons which penetrate the gas and get detected. Gammas are usually much more likely to be detected this way than by direct interaction with the gas. The thickness of the walls affects the probability that a gamma will interact and be detected.

$$\begin{aligned}
 \text{5.11} \quad \text{x-ray energy} &= 0.005 \times \text{electrical energy.} \\
 \text{absorbed energy} &= 0.1 \times \text{x-ray energy.} \\
 &= 0.1 \times 0.005 IV t \\
 &= (5 \times 10^{-4}) \times (100 \times 10^{-3} \text{ A}) \times (100 \times 10^3 \text{ V}) \times (0.01 \text{ s}) \\
 &= 0.5 \text{ J.} \\
 \text{Patient dose} &= \frac{0.5 \text{ J}}{70 \text{ kg}} = 7 \text{ mGy.}
 \end{aligned}$$

5.12 The dose received in a year (from a long-lived radioactive element such as radium which has an essentially constant activity during that time) is given by the dose rate multiplied by the time.

The dose rate is given by the activity R (i.e. the number of disintegrations per time) multiplied by the energy E associated with each disintegration (multiplied where appropriate, by a factor F describing what fraction of the energy is deposited in body tissue) divided by the mass of the person (or organ) in which the energy is deposited:

$$\frac{D}{t} = \frac{REF}{m}$$

1 g radium has an activity of 3.7×10^{10} Bq, so 1 mg will have an activity of 3.7×10^4 Bq or $3.7 \times 10^4 \text{ s}^{-1}$.

So the dose rate is

$$\begin{aligned}
 \frac{D}{t} &= \frac{3.7 \times 10^4 \text{ s}^{-1} \times 4.8 \text{ MeV} \times 1}{70 \text{ kg}} \\
 &= \frac{3.7 \times 10^4 (3600 \times 24 \times 365) \text{ y}^{-1} \times 4.8 \times 10^6 \times 1.6 \times 10^{-19} \text{ J}}{70 \text{ kg}} \\
 &= 13 \text{ mGy.y}^{-1}.
 \end{aligned}$$

CHAPTER AN6

$$6.1 \quad \lambda_0 = \frac{hc}{eV} = \frac{1.24 \text{ keV}\cdot\text{nm}}{E}$$

Express each photon energy E in electronvolts to get

$$(a) \lambda_0 = \frac{1.24 \text{ keV}\cdot\text{nm}}{10 \text{ keV}} = 0.12 \text{ nm.}$$

$$(b) \lambda_0 = 0.012 \text{ nm.}$$

$$(c) \lambda_0 = 6.2 \times 10^{-14} \text{ m.}$$

$$(d) \lambda_0 = 1.2 \times 10^{-15} \text{ m.}$$

6.2 K_α : transition from L to K: approximate energy = $(20.0 - 2.8) \text{ keV} = 17.2 \text{ keV}$

K_β : transition from M to K: approximate energy = $(20.0 - 0.5) \text{ keV} = 19.5 \text{ keV}$.

Wavelengths: K_α : $\lambda = 7.2 \times 10^{-11} \text{ m}$. K_β : $\lambda = 6.3 \times 10^{-11} \text{ m}$.

To obtain a K_α or K_β line we must knock a K electron out. This requires more than 20 keV, so the potential difference must be at least 20 kV. This is consistent with the experimental curves.
