& some 18 + 10

Chapter 19 Using the Atom Past Paper Question Booklet

2864 Jan 2001

6 Cobalt-60 is a radioisotope which emits gamma photons of energy 1.2 MeV. Calculate the mass loss due to the emission of one gamma photon.

$E = mc^2$

$\therefore m = \frac{E}{c^2} = \frac{1.2\times10^{6}\times1.6\times10^{-19}}{(3\times10^{8})^2}$

mass = (−) 2.1×10^{-30} kg [3]

8 The risk of one person developing cancer from exposure to ionising radiation in their lifetime is 5% per sievert. Suppose that a worker at a nuclear processing plant has an average equivalent dose of 0.01 sievert per year. Calculate the risk of the worker developing cancer as a consequence of working at the plant for 30 years.

$0.01\times30\times5\%$

risk = 1.5 % [2]

2864 June 2001

2 A photon can convert into a positron and an electron, each of mass 9.11 x 10^{-31} kg. Calculate the minimum energy for a photon to be able to do this.

$E = mc^2 = 2\times9.11\times10^{-31}\times(3\times10^{8})^2 =$

photon energy = 1.64×10^{-13} J [2]

3 Which of the units in the list below is the correct choice for the activity of a radioactive source?

Bq g cm^{-2} Gy Sv

(1 Bq = 1 decay per second)

Bq [1]

11 This question is about the radioactive decay of plutonium

(a) Plutonium-238 is an emitter of alpha particles. Complete the equation for its decay.

$$^{238}_{94}\text{Pu} \rightarrow {}^{234}_{92}\text{U} + {}^{4}_{2}\text{He}$$

Study Fig. 11.1.

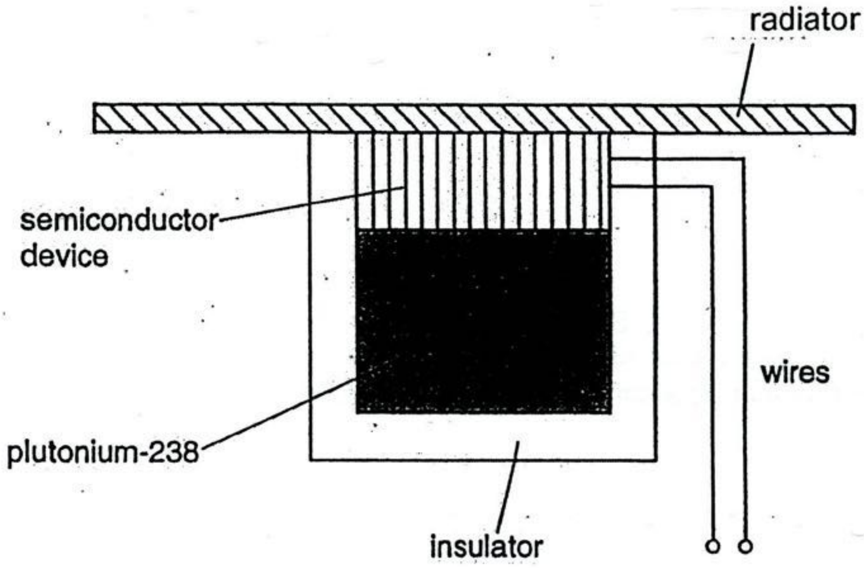

Fig.11.1

Energy from the decay of the plutonium makes the plutonium hot.
This produces a temperature difference across the semiconductor device as energy is conducted through it and radiated away.
The temperature difference across the semiconductor device generates an emf.

(b) Describe, in detail, how the decay of the plutonium results in a rise of its temperature.

The uranium nucleus has a more negative binding energy than plutonium. The energy (and hence mass) lost is carried away as the kinetic energy of the alpha particle. This then collides with other nuclei transferring energy to them increasing their thermal energy and hence temperature.

[4]

(c) Each alpha particle emitted by the decay of plutonium-238 has an energy of 8.8×10^{-13}J. 15% of the energy from the decay of the plutonium appears as electrical output from the semiconductor device.
The output power of the semiconductor device is 100W.

(i) Show that the plutonium must decay at a rate of approximately 10^{15}Bq.

Energy needed per second $= \frac{100\text{W}}{0.15} = 666.7\ \text{J s}^{-1}$

Activity $= \frac{666.7\ \text{J s}^{-1}}{8.8 \times 10^{-13}\ \text{J}} = 7.6 \times 10^{14}$ Bq $\approx 10^{15}$ Bq

[2]

(ii) Plutonium-238 has a half-life of 86 years. By calculating a value for its decay constant, calculate the mass of plutonium required for an activity of 10^{15}Bq.
1 u = 1.66×10^{-27}kg

$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}} = \frac{\ln 2}{86 \times 365.25 \times 24 \times 60 \times 60} = 2.55 \times 10^{-10}\ \text{s}^{-1}$

OR $= \ln 2 / 86 \times 3.16 \times 10^{7} = 2.55 \times 10^{-10}\ \text{s}^{-1}$

↑ on data sheet.

$A = \lambda N$

mass = 1.6 kg [3]

$\therefore N = A/\lambda = 10^{15} / 2.55 \times 10^{-10}$

$= 3.92 \times 10^{24}$ nuclei

$m = 1.66 \times 10^{-27} \times 238 \times 3.92 \times 10^{24}$

$= 1.55$ kg

2864 Jan 2004

9 The graph of Fig. 9.1 shows how the average binding energy per nucleon varies with nucleon number.

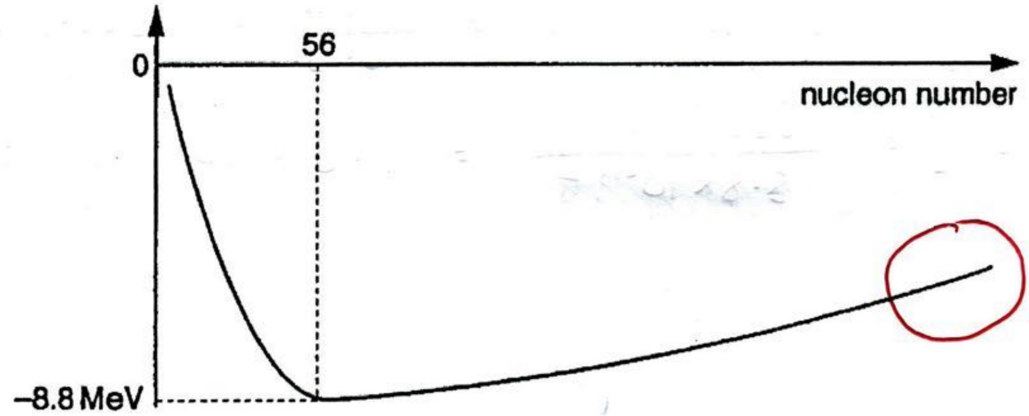

Fig. 9.1

(a) Circle the region of the graph which contains the fissile elements used for generating electricity by a nuclear fission chain reaction. [1]

(b) The average binding energy per nucleon for a nucleus of iron-56 is –8.8 MeV.

(i) Show that the energy required to separate all the nucleons in a single nucleus of iron-56 is about 1×10^{-10} J.

$e = 1.6 \times 10^{-19}$ C

$= 8.8 \times 10^{6} \times 1.6 \times 10^{-19} \times 56$

$= 7.9 \times 10^{-11}$ J $\approx 10^{-10}$ J

[2]

(ii) Calculate the change of mass corresponding to the energy change of **(b)(i)**.

$c = 3.0 \times 10^{8}$ m s^{-1}

$E = mc^2 \therefore m = \frac{E}{c^2} = \frac{7.9 \times 10^{-11}}{(3 \times 10^{8})^2} =$

change of mass = 8.8×10^{-28} kg [2]

12 This question is about the risks involved with dental X-ray photography.

(a) A single dental X-ray exposes a patient to a dose equivalent of 16 μSv. ← 10^{-6}
A dose equivalent of 1 Sv gives the patient a 3% probability of developing cancer in a lifetime.

(i) Suppose that a patient has two dental X-rays each year for sixty years. ← 2×60 = 120 X-rays
Show that the associated risk of developing cancer is about 0.006%.

$$\text{Risk} = 16\times10^{-6}\times2\times60\times3\%$$
$$= \underline{\underline{5.76\times10^{-3}\,\%}} \approx 0.006\,\%$$

[3]

(ii) Suppose that everyone in the UK has two dental X-rays each year for sixty years. Calculate the number of people in the UK who are likely to develop cancer as a result of these X-rays.
Assume that the population of the UK is 55 million.

$$= 55\times10^{6}\times\frac{0.006}{100} = 3300$$

(OR 3170 for 5.76×10^{-3})

number = ...3300... [1]

(iii) The annual dose equivalent from background radiation in the UK is about 2 mSv. By comparing this with the dose equivalent from dental X-rays, discuss the risks to a patient of undergoing dental X-rays for a lifetime. Support your answer with calculations.

$$\frac{\text{Background dose}}{\text{X-ray dose}} = \frac{2\times10^{-3}\ \text{Sv year}^{-1}}{32\times10^{-6}\ \text{Sv year}^{-1}} = 62.5$$

The background dose is 62.5 × greater than the x-ray dose so the risk of developing cancer will be much much greater. Only around 1 in 60 cancers are likely to be due to X-rays.

[4]

(b) The table gives data for the dose equivalent for the dentist at different distances from an X-ray source, for a single dental X-ray.

distance / m	dose equivalent / μSv	distance^2 × dose equivalent
0.25	2.6	0·1625 = 0·16 2s.f.
0.41	0.95	0·1597 = 0·16 2s.f.
0.77	0.27	0·1601 = 0·16 2s.f.

The dose equivalent for the dentist is inversely proportional to the square of the distance from the X-ray source.

(i) Propose and carry out a test to show that the data in the table fit this relationship. Use the blank column of the table.

dose equivalent = $k/\text{distance}^2$

∴ k = dose equivalent × distance^2

If k is constant, then the data fits. [3]

(ii) Suggest **two** reasons why the dose equivalent for the dentist varies with distance from the X-ray source in this way.

The X-rays spread out from a point source and are not absorbed by the air. At double the distance they spread over 4x the area so the intensity is 1/4. [2]

(iii) A dentist is told to limit his dose equivalent from the X-ray source to 0.20 mSv per year. He has to give 4000 dental X-rays in a year.

Use the relationship between dose equivalent and distance to calculate the minimum distance he must keep from the X-ray source each time it is used.

does equivalent per X-ray = $\frac{0{\cdot}20\times10^{-3}}{4000} = 5\times10^{-8}$ Sv $= 0{\cdot}05\,\mu$Sv

distance = $\sqrt{\frac{0{\cdot}16}{\text{dose eq.}}} = \sqrt{0{\cdot}16/0{\cdot}05} = 1{\cdot}79$m

distance = 1·8 m [2]

2864 June 2004

4 A worker in a nuclear processing plant receives an average absorbed dose of 30 mSv per year from the radioactive materials he works with. He works in the processing plant for 40 years.

(a) Which of the following (**A, B, C** or **D**) is the best estimate for the **total** energy absorbed by the worker's body from the radioactive materials he works with for 40 years? The quality factor of the radiation is 1.0 and his body mass is 80 kg.

A 0.01 J　　**B** 1.0 J　　**C** 100 J　　**D** 100 000 J

$30 \times 10^{-3} \times 40 \times 80 = 96\ J$

answer ......C...... [1]

(b) The risk of developing cancer from ionising radiation is 3% per sievert per year. Calculate the risk of cancer to the worker of working at the plant for 40 years.

$30 \times 10^{-3} \times 40 \times 3\% =$

risk = ...3·6...... % [1]

7 Caesium-133 and caesium-128 are different isotopes of the same element.

(a) Complete the sentence below by choosing the appropriate word from this list.

electrons　　**neutrons**　　**protons**

An atom of caesium-133 has 5 more ...neutrons... than an atom of caesium-128. [1]

(b) Caesium-133 is a stable isotope. It does not undergo radioactive decay. Caesium-128 is unstable and is radioactive.

Which of the following (**A, B** or **C**) is the most likely emission from the radioactive decay of caesium-128?

A alpha particle　　**B** proton　　**C** positron

answer ......C...... [1]

Cs - 128 is short of neutrons compared to stable Cs - 133 so.

$p \rightarrow n + e^+ + \nu$ (β^+ decay)

11 This question is about the dangers of plutonium in nuclear reactor waste.

Small specks of plutonium-239 have been known to escape from nuclear waste. Fortunately, their radioactivity makes them relatively easy to detect in the environment.

(a) Plutonium-239 decays naturally into uranium-235 by emitting an alpha particle.

(i) Complete the equation representing the decay of plutonium-239.

$$^{239}_{94}\text{Pu} \longrightarrow {}^{235}_{92}\text{U} + {}^{4}_{2}\text{He}$$ [2]

(ii) The half-life of plutonium-239 is 7.6×10^{11} s.
Show that a sample containing only 2.5×10^{14} nuclei of plutonium-239 can be detected when the background count is 1 Bq.

$\lambda = \ln 2 / t_{\frac{1}{2}} = \ln 2 / 7.6 \times 10^{11} = 9.12 \times 10^{-13}\ s^{-1}$

$A = \lambda N = 9.12 \times 10^{-13} \times 2.5 \times 10^{14} = 228$ Bq

which is much greater than the background count. [2]

(iii) Calculate the mass of 2.5×10^{14} nuclei of plutonium-239.

$1\ u = 1.7 \times 10^{-27}$ kg

$m = 239 \times 1.7 \times 10^{-27} \times 2.5 \times 10^{14} = 1.02 \times 10^{-10}$ kg

mass = 1.0×10^{-10} kg [1]

(iv) Such a small speck of plutonium could easily be breathed in and become stuck in lung tissue. This gives a large increase in the risk of developing lung cancer.
By considering the properties of alpha particles, explain why the risk is increased.

Alpha particles are easily absorbed by body tissue as they have a short range. They are also very ionizing giving them a high quality factor. As a result they cause a lot of damage to cells causing them to mutate

[3]

(b) Plutonium can be made to undergo fission by bombarding it with a beam of protons. A typical reaction is shown below.

$$^{239}_{94}Pu + ^{1}_{1}p \rightarrow ^{133}_{53}I + ^{99}_{42}Mo + \text{neutrons}$$

n : 145 0 80 57   145 − (80+57) = 8

(i) Calculate the number of neutrons produced by this reaction.

number of neutrons = ...8.......... [1]

(ii) For this reaction to work, a proton must approach to within 7.4×10^{-14} m of the centre of the plutonium nucleus.
By considering the electrical potential energy of the proton as it approaches the nucleus, calculate the minimum kinetic energy of the proton.

charge of nucleus = $+1.5 \times 10^{-17}$ C
charge of proton = $+1.6 \times 10^{-19}$ C
electric force constant $k = 9.0 \times 10^{9}\ \text{N m}^2\text{C}^{-2}$

$$E_e = \frac{kQq}{r} = \frac{9\times10^{9} \times 1.5\times10^{-17} \times 1.6\times10^{-19}}{7.4\times10^{-14}} =$$

kinetic energy = ...2.9×10^{-13}...... J [2]

2864 Jan 2005

2 A nucleus of hydrogen-3 can be formed when a neutron is absorbed by a nucleus of hydrogen-2.

$$^{2}_{1}H + ^{1}_{0}n \rightarrow ^{3}_{1}H$$

The table gives the masses of the three particles in atomic mass units (u).

particle	mass/u
$^{1}_{0}n$	1.00867
$^{2}_{1}H$	2.00141
$^{3}_{1}H$	3.00160

Show that about 1×10^{-12} J of energy is released for each nucleus of hydrogen-3 created in this way.

$u = 1.7 \times 10^{-27}$ kg
$c = 3.0 \times 10^{8}\ \text{m s}^{-1}$

$\Delta m = ((2.00141 + 1.00867) - 3.00160)\ u$
$= -0.00848$
$= 0.00848 \times 1.7\times10^{-27} = 1.44\times10^{-29}$ kg

$E = mc^2 = 1.44\times10^{-29} \times (3\times10^{8})^2$
$= \underline{1.3\times10^{-12}\ J}$

[3]

6 The graph of Fig. 6.1 shows the variation of binding energy per nucleon with the total number of nucleons in a nucleus.

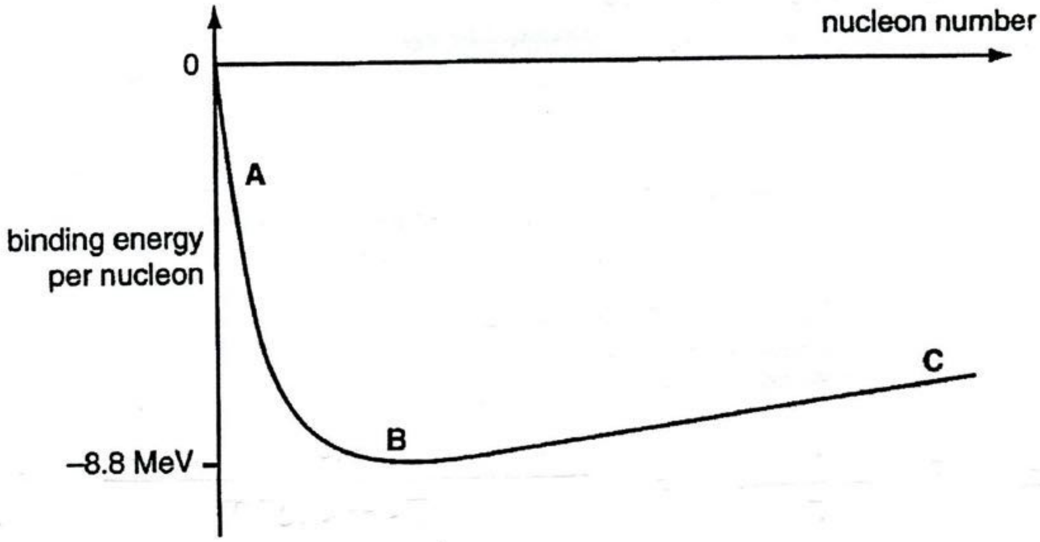

Fig. 6.1

Three regions (**A**, **B** and **C**) are marked on the graph.

State the region (**A**, **B** or **C**) which

(a) contains the nucleon number 56 ....B.......... [1]

(b) contains nuclei which can be used to provide energy by nuclear fusion ....A.......... [1]

(c) contains nuclei which undergo nuclear fission. ....C.......... [1]

9 This question is about the risk to a patient of using a radioactive tracer for diagnosis.

The isotope iodine-131 is a beta emitter which decays to a stable isotope of xenon.

(a) **(i)** Complete the equation for the beta decay of iodine-131.

$$^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e} + {}^{0}_{0}\bar{\nu}$$

[2]

(ii) Name the particle represented by the symbol $\bar{\nu}$.

name ...antineutrino...[1]

(b) The half-life of iodine-131 is 8.1 days.

Show that the decay constant of iodine-131 is about $1 \times 10^{-6}\,\text{s}^{-1}$.

1 day = 86 400 s

$\lambda = \ln 2 / t_{\frac{1}{2}} = \ln 2 / 8.1 \times 86400$

$= 9.9 \times 10^{-7}\ \text{s}^{-1}$

[2]

(c) A patient is injected with a freshly made solution of iodine-131. The iodine-131 becomes concentrated in the thyroid gland. The initial activity of the iodine-131 in the thyroid gland is then 2.5×10^{5} Bq.

(i) Show that the initial number of iodine-131 nuclei in the thyroid gland is about 2.5×10^{11}.

$A = \lambda N \quad \therefore \quad N = A/\lambda = \dfrac{2.5 \times 10^{5}}{9.9 \times 10^{-7}} = 2.52 \times 10^{11}$

[2]

(ii) The maximum energy of the beta particles emitted by iodine-131 is 0.81 MeV. The mass of the thyroid gland is 0.060 kg.

Show that the dose equivalent received by the gland after all the iodine-131 has decayed can be no more than 0.5 Sv.

$0.81 \times 10^{6} \times 1.6 \times 10^{-19} \times 2.52 \times 10^{11} = 0.0327\ \text{J}$

$\dfrac{0.0327\ \text{J}}{0.060\ \text{kg}} = 0.54\ \text{Gy}$ & quality factor = 1

$\therefore 0.54\ \text{Sv}$ if all beta particles are absorbed.

[2]

(iii) The risk to the patient of developing cancer is 3% per sievert. The extra risk of developing cancer as a result of exposure to the iodine-131 is to be limited to 0.1%.

Calculate the maximum number of iodine-131 nuclei which should be allowed to settle in the patient's thyroid gland during the treatment.

Max dose eq. $= \frac{0.1\%}{3\%} \times 1\ Sv = 0.0333\ Sv$

2.5×10^{11} nuclei give dose of 0.54 Sv

$\therefore$ Max nuclei $= \frac{0.0333}{0.54} \times 2.5 \times 10^{11} =$

number of nuclei = 1.5×10^{10} [2]

(d) Suggest reasons why the calculations made in **(c)(ii)** lead to an over-estimate of the dose equivalent received by the gland.

0.81 MeV is the maximum beta particle energy, many will have less. Not all the beta particles will be absorbed by the gland.

[2]

2864 June 2005

13 This question is about calculating the risk to workers exposed to radioactive materials.

Disposable surgical instruments are sterilised by gamma photons from a sample of cobalt-60. The instruments in their airtight plastic bags are packed into boxes and placed on the conveyor belt , as shown in Fig. 13.1.

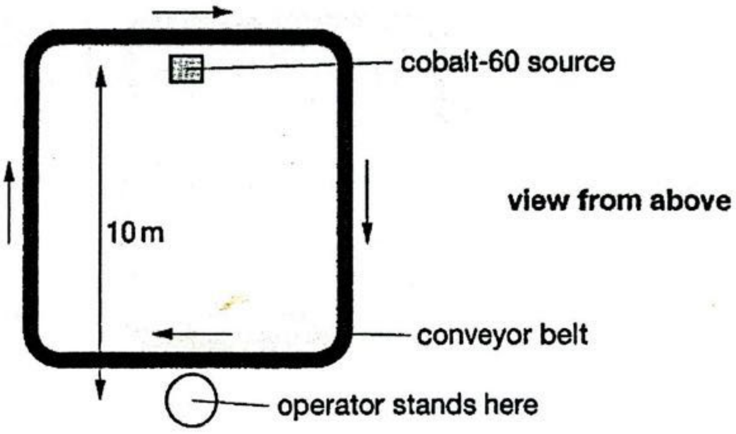

Fig. 13.1

(a) Operators are required to stand on a spot that is 10 m from the cobalt-60 source. Boxes that they load onto the conveyor belt pass much closer to the cobalt-60, and are exposed to a high intensity of gamma photons. The intensity I of gamma photons at a distance d from a source which emits photons at a rate A is given by the expression

$$I = \frac{A}{4\pi d^2}.$$

(i) The source emits gamma photons at a rate of 2.4×10^{16} Bq.

Show that the intensity of gamma photons for the operators would be about 2×10^{13} Bq m^{-2} in the absence of shielding.

$$I = \frac{2.4 \times 10^{16}}{4\pi \times 10^2} = 1.91 \times 10^{13} \text{ Bq m}^{-2}$$

[1]

(ii) Explain why the intensity of gamma photons decreases with increasing distance from the source.

The gamma photons spread out in all directions at double the distance they cover 4x the area so are 1/4 the intensity.

[2]

(iii) A nucleus of cobalt-60 releases a beta particle when it decays, quickly followed by a pair of gamma photons.

Explain why the beta particles contribute very little to the absorbed dose of the operator.

Beta particles are absorbed by air so they have a short range.

[1]

(b) In order to reduce the intensity of gamma photons for the operators to a safe level, a 1.2 m thick wall of concrete is placed between them and the source, as shown in Fig. 13.2.

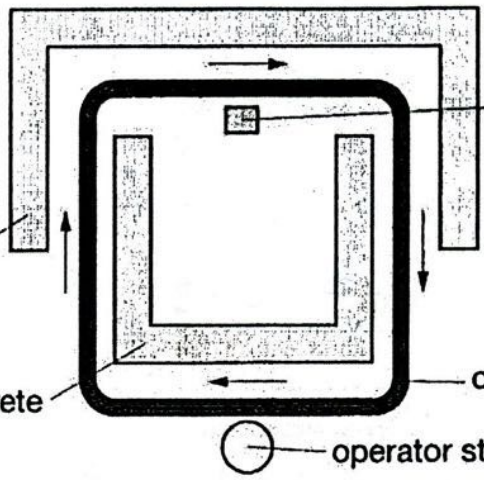

Fig. 13.2

(i) The intensity of the photons is halved for each 4.0×10^{-2} m thickness of concrete that they pass through.

Show that the 1.2 m thickness of concrete reduces the intensity of gamma photons for the operator to about 2×10^{4} Bq m^{-2}.

Number of half-thicknesses $= 1.2 / 4 \times 10^{-2} = 30$

$I = I_0 \times 0.5^{30} = 1.9 \times 10^{13} \times 0.5^{30} = \underline{1.8 \times 10^{4}}$ Bq m^{-2} [2]

(ii) Each operator presents an average area of 0.80 m^2 for absorption of the gamma photons.

If all of the photons are absorbed by an operator, show that the operator absorbs about 1×10^{-4} J of energy in each eight hour working day.

energy of photons = 1.8×10^{-13} J

$E = 1.8 \times 10^{4} \times 0.80 \times 1.8 \times 10^{-13} \times 3600 \times 8$

$= 7.5 \times 10^{-5}$ J $\approx 1 \times 10^{-4}$ J [2]

(iii) The average mass of an operator is 75 kg, and the gamma photons have a quality factor of 1.

Show that the absorbed dose of the operator is below the recommended safe limit of 4.0×10^{-6} Sv per day.

Dose $= \dfrac{7.5 \times 10^{-5} \times 1}{75} = 1.0 \times 10^{-6}$ Sv per day [2]

2864 Jan 2006

10 Radon-222 is a naturally occurring gas which is radioactive. It is the biggest source of background radiation in the UK, contributing almost half of the average absorbed dose for people who live here.

(a) Radon-222 decays by emitting an alpha particle, becoming polonium-218.
Complete the nuclear equation for the decay of radon-222.

$$^{222}_{86}\text{Rn} \rightarrow \, ^{218}_{84}\text{Po} + \, ^{4}_{2}\text{He}$$ [2]

(b) Polonium-218 has a half-life of only 3 minutes. Its decay produces a cascade of short-lived isotopes.
Here is the incomplete nuclear equation for one of the decays in the cascade.

$$^{214}_{83}\text{Bi} \rightarrow \, ^{214}_{84}\text{Po} + X + Y$$

X and Y are particles emitted in the decay.

(i) Explain why one of the particles X or Y could be an electron.

There is no change in nucleon number (214) but proton number increases so a -1 is needed to balance the nuclear equation an an electron is $^{0}_{-1}e$

[2]

(ii) If X is an electron, suggest why Y could be an antineutrino.

It must be an anti lepton to balance lepton number and nucleon and proton numbers must be zero ⇒ $^{0}_{0}\bar{\nu}$

[1]

(c) Alpha particles are emitted during the cascade of decays from radon-222.
Estimates of the cancer risk due to breathing in radon-222 need only consider these alpha particles.

(i) Suggest why gamma photons emitted in the cascade can be neglected when estimating the risk of cancer.

Gamma photons are not easily absorbed (they have a large range) and have a low quality factor (are not very ionizing)

[2]

(ii) The alpha particles emitted by the decay of a radon-222 nucleus have a combined energy of 1.0×10^{-12} J. This contributes 47% of the annual background radiation dose of 2.5 mSv per year.
Show that about 130 nuclei of radon-222 must decay per second in the body of a person of mass 70 kg to provide this dose.

quality factor of alpha particles = 20
1 year = 3.2×10^7 s

47% of 2.5 mSv = 1.18 mSv per year

Dose rate = $\frac{1.18 \times 10^{-3}}{3.16 \times 10^7}$ = 3.73×10^{-11} Sv s^{-1}

Dose rate = $\frac{\text{Activity} \times \text{Energy} \times \text{QF}}{\text{mass}}$

$\therefore$ Activity = $\frac{\text{Dose Rate} \times \text{mass}}{\text{Energy} \times \text{QF}}$ = $\frac{3.73 \times 10^{-11} \times 70}{1.0 \times 10^{-12} \times 20}$ = 131 Bq

[3]

(d) (i) Radon-222 has a half-life of 3.8 days.
Show that the decay constant is about 2×10^{-6} s^{-1}.

$\lambda = \frac{\ln 2}{t_{\frac{1}{2}}} = \frac{\ln 2}{3.8 \times 24 \times 3600} = 2.11 \times 10^{-6}$ s^{-1}

[2]

(ii) Calculate the number of radon-222 nuclei required for 130 decays per second.

$A = \lambda N \quad \therefore N = A/\lambda$

$= 130/2.11 \times 10^{-6} = 6.16 \times 10^7$

number = 6.2×10^7 [2]

2864 Jan 2007

9 This question is about the risks involved in using radioactive material in smoke detectors. Fig. 9.1 shows a cross-section through a smoke detector mounted on a ceiling.

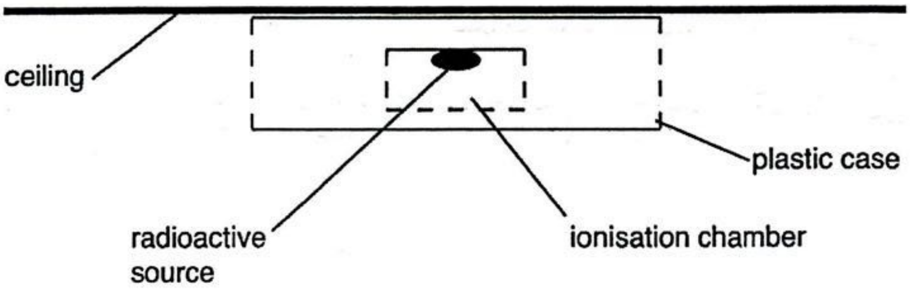

Fig. 9.1

The smoke detector uses americium-241, an emitter of alpha particles, to ionise air inside the ionisation chamber. Any smoke in the chamber absorbs the ions, reducing the conductivity of the air in the chamber.

(a) A typical smoke detector contains 2.0×10^{-10} kg of americium-241.

(i) Show that 2.0×10^{-10} kg of americium-241 contains about 5×10^{14} nuclei of the isotope.

$u = 1.7 \times 10^{-27}$ kg

$$N = \frac{2.0 \times 10^{-10}}{1.7 \times 10^{-27} \times 241} = 4.9 \times 10^{14}$$

[2]

(ii) Americium-241 has a half-life of 1.5×10^{10} s.
Show that the decay constant of the radioisotope is about $5 \times 10^{-11}\ s^{-1}$.

$$\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{1.5 \times 10^{10}} = 4.62 \times 10^{-11}\ s^{-1}$$

[1]

(iii) Calculate the activity of the americium-241 in the smoke detector.

$$A = N\lambda = 4.9 \times 10^{14} \times 4.62 \times 10^{-11}$$

activity = 2.3×10^{4} Bq [2]

(b) Nuclei of americium-241 decay by emitting alpha particles. Suggest why the radioactive material in the smoke detector is not a hazard when the isotope is inside the detector.

Alpha particles are absorbed by the case as they are not very penetrating.

[2]

(c) In the event of a fire, some of the radioactive material in the detector could be breathed in by someone close by. The risk of developing cancer from this event is modelled as follows

- 1% of the radioactive material (2.0×10^{-12} kg) is breathed in
- the material is evenly spread through the person's lungs, of mass 2.0 kg.

(i) Use your answer to **(a)(iii)** to show that the annual dose equivalent from the event for this person is about 0.1 Sv per year.

energy of alpha particles = 8.7×10^{-13} J
quality factor for alpha particles = 20
1 year = 3.2×10^7 s

$$\text{Dose} = \frac{\text{Activity} \times \text{Energy} \times \text{QF} \times \text{time}}{\text{mass}}$$

$$= \frac{2.3 \times 10^4 \times 0.01 \times 8.7 \times 10^{-13} \times 20 \times 3.2 \times 10^7}{2.0}$$

$= 0.064$ Sv per year.

[2]

(ii) The risk of developing cancer from radioactive materials is 3% Sv^{-1}.
Comment on the risks posed by the radioactive materials in smoke detectors given by this model. Support your answer with calculations.

$t_{\frac{1}{2}} = 1.5 \times 10^{10} / 3.2 \times 10^7$
$= 470$ yrs

So activity constant for life time of person.

Risk $= 0.064 \times 50$ yrs $\times 3\%$

$\approx 10\%$ risk over 50 yrs

This is large but assumes the americium-241 remains in the lungs.

[3]

2864 June 2007

5 Strontium-90 is a radioactive waste product of nuclear power stations. Strontium-90 emits beta particles of energy up to 0.54 MeV.

(a) Should any of this isotope get into our food, it would be quickly absorbed into bones and teeth.

Explain why these beta particles are more of a risk to humans than gamma photons of the same energy.

Beta particles are more easily absorbed as they are more ionizing so will result in a larger absorbed dose.

[2]

(b) Strontium-90 has a decay constant of $7.8 \times 10^{-10}\,s^{-1}$. An accident at a nuclear power station results in strontium-90 with activity of 300 kBq being absorbed into a person's bones. Calculate the activity 56 years later.

1 year = 3.2×10^7 s

$$A = A_0 e^{-\lambda t} = 300 \times 10^3 \times e^{-7.8 \times 10^{-10} \times 56 \times 3.2 \times 10^7} =$$

activity = 7.4×10^4 Bq [2]

8 The recommended maximum absorbed dose limit for someone who works with radioactive materials is 20 mSv per year. The risk of developing cancer from radioactivity is 3% per sievert. Calculate the increased risk of developing cancer for someone who has an absorbed dose of 20 mSv per year for 40 years.

risk = $20 \times 10^{-3} \times 40 \times 3\%$ =

risk = 2.4 % [2]

10

In this section, four marks are available for the quality of written communication.

This question is about a model of the nucleus.

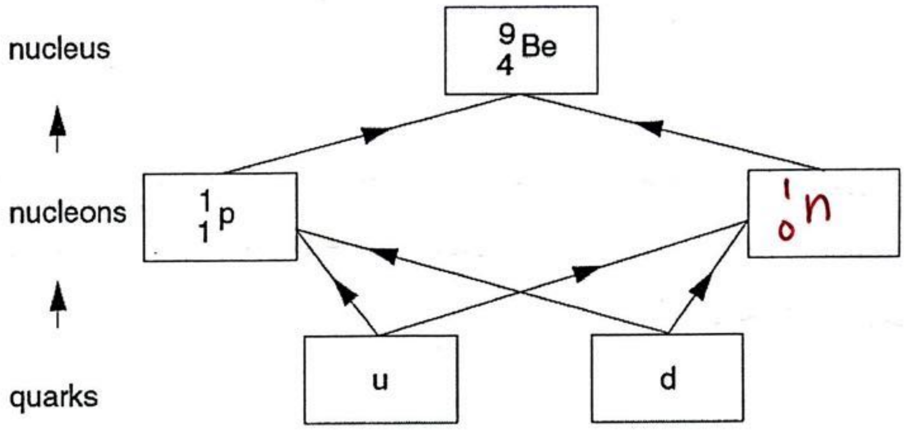

Fig. 10.1

Fig 10.1 shows how each nucleon can be modelled as containing two different types of quark. In turn, a nucleus of beryllium can be modelled as containing two different types of nucleon.

(a) The left-hand nucleon box in Fig. 10.1 contains $^{1}_{1}$p. Complete the other nucleon box. [1]

(b) Each quark has a different charge. The u quark has charge $+^{2}/_{3}e$ and the d quark has charge $-^{1}/_{3}e$, where $e = 1.6 \times 10^{-19}$ C.

(i) State the combination of u and d quarks required to make the nucleon $^{1}_{1}$p.

Justify your answer.

uud $= \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1 =$ p

[2]

(ii) Particles other than nucleons can be modelled as pairs of quarks (u, d) and anti-quarks ($\bar{u}$, $\bar{d}$).

For example, the positive π^{+} meson can be modelled as $u\bar{d}$.

Write down the **two** quark-antiquark pairs which can model a neutral π^{0} meson.

$u\bar{u}$, $d\bar{d}$

[1]

(c) The mass of a single $^{9}_{4}$Be nucleus is 1.4966×10^{-26} kg. This is slightly less than the total mass of its separate nucleons.

(i) How many protons and neutrons are there in a single nucleus of $^{9}_{4}$Be?

number of protons = ...4....

number of neutrons = ...5....

[2]

(ii) Show that the mass of a $^{9}_{4}$Be nucleus is about 1×10^{-28} kg less than the mass of its separate nucleons.

$m_{proton} = 1.673 \times 10^{-27}$ kg

$m_{neutron} = 1.675 \times 10^{-27}$ kg

$\Delta m = 1.4966 \times 10^{-26} - (4 \times 1.673 \times 10^{-27} + 5 \times 1.675 \times 10^{-27})$

$= -1.01 \times 10^{-28}$ kg

[2]

(iii) Hence calculate the average binding energy per nucleon, in MeV, for a nucleus of $^{9}_{4}$Be.

$c = 3.0 \times 10^{8}\ \text{m s}^{-1}$

$e = 1.6 \times 10^{-19}$ C

$E = mc^2 = -1.01 \times 10^{-28} \times (3 \times 10^{8})^2 = -9.09 \times 10^{-12}$ J

$= \frac{-9.09 \times 10^{-12}}{1.6 \times 10^{-19}} = -56.8$ MeV

$\frac{-56.8}{9} =$ average binding energy per nucleon = ...(–) 6.3.... MeV [3]

(d) The nucleons in a nucleus are bound to each other by the strong force.

Explain why this requires the mass of the nucleus to be **less** than the mass of its separate nucleons.

The nucleus has less energy (as the binding energy is negative) and hence less mass as $m = E/c^2$.

[2]

2864 Jan 2008

2 Gamma photons with enough energy can make a nucleus of hydrogen-2 disintegrate into a proton and a neutron.

$$^{2}_{1}H + ^{0}_{0}\gamma \rightarrow ^{1}_{1}p + ^{1}_{0}n$$

particle	mass/ u
hydrogen-2 nucleus	2.01355
proton	1.00728
neutron	1.00867

(a) Use the table to show that the mass of a hydrogen-2 nucleus is about 4×10^{-30} kg less than the combined mass of a separate neutron and proton.

$u = 1.7 \times 10^{-27}$ kg

$2.01355 - (1.00728 + 1.00867) = -2.4 \times 10^{-3}\ u$

$= -2.4 \times 10^{-3} \times 1.7 \times 10^{-27} = -4.1 \times 10^{-30}$ kg

[2]

(b) Calculate the minimum energy of a gamma photon for the reaction to take place.

$c = 3.0 \times 10^{8}\ \mathrm{m\,s^{-1}}$

$E = mc^2 = 4.1 \times 10^{-30} \times (3 \times 10^{8})^2 =$

photon energy = 3.7×10^{-13} J [1]

12 This question is about neutrons from a nuclear reactor in a power station.

Fig. 12.1 shows the construction of a detector of neutrons from the reactor.

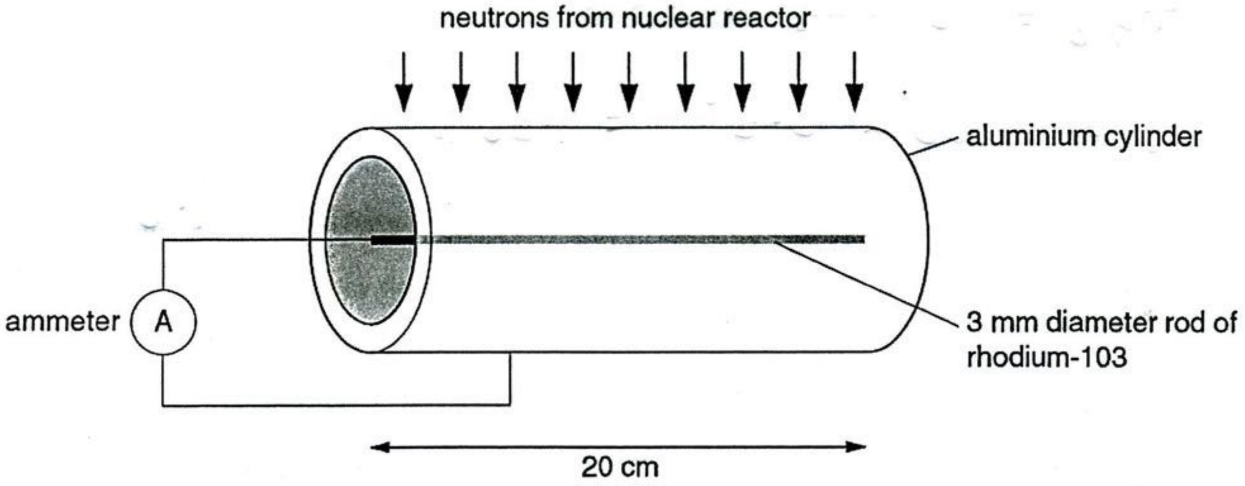

Fig. 12.1

A rod of rhodium-103 at the centre of a metal cylinder absorbs neutrons to become rhodium-104. The rhodium-104 decays with a half-life of 43 s, emitting 2.44 MeV beta particles. These are absorbed by the cylinder giving a current in the ammeter.

(a) (i) Complete the nuclear equation to represent the process of neutron absorption and beta emission.

$$^{103}_{45}\text{Rh} + ^{1}_{0}\text{n} \rightarrow ^{104}_{45}\text{Rh} \rightarrow ^{104}_{46}\text{Pd} + ^{0}_{-1}\text{e} + ^{0}_{0}\bar{\nu}$$

[1]

(ii) Suggest why most of the neutrons pass through the aluminium cylinder but all of the beta particles are absorbed by it.

neutrons are neutral so only interact with a nucleus in a head-on collision. / Charged electrons scatter without needing to get close to a nucleus.

[1]

(b) The detector produces one beta particle for every 6 neutrons which arrive at the rod of rhodium-103. Calculate the rate at which neutrons are arriving at the rod when the ammeter reads 42 nA.

$e = 1.6 \times 10^{-19}$ C

$$\text{rate} = \frac{42 \times 10^{-9}}{1.6 \times 10^{-19}} \times 6 =$$

neutron rate = 1.6×10^{12} s^{-1} [2]

(c) The reactor is shielded by 48 cm of concrete. Half of the neutrons from the reactor are absorbed by 8.0 cm of concrete. Calculate the percentage of the neutrons transmitted through 48 cm of concrete.

$48/8 = 6$ half-thicknesses

$\% = 100 \times 0.5^6 = 1.56\ \%$

percentage transmitted = ...1.6...... % [2]

(d) The maximum permitted dose equivalent for people who work with radiation is 20 mSv per year over five years.

(i) The risk of developing cancer due to exposure to radiation is 3% per Sv.

Estimate the risk to a worker who receives the maximum permitted dose equivalent for five years.

risk $= 20 \times 10^{-3} \times 5 \times 3\% =$

risk = ...0.3...... % [1]

(ii) Calculate the average rate at which a 65 kg person must absorb 0.025 eV neutrons from the reactor over a year to reach the maximum permitted dose equivalent.

Neutrons have quality factor of 10.

1 year = 3.2×10^7 s
1 eV = 1.6×10^{-19} J

$$\text{dose} = \frac{\text{rate} \times \text{time} \times \text{energy} \times \text{QF}}{\text{mass}}$$

$$\therefore \text{rate} = \frac{\text{dose} \times \text{mass}}{\text{time} \times \text{energy} \times \text{QF}} = \frac{20 \times 10^{-3} \times 65}{3.2 \times 10^7 \times 0.025 \times 1.6 \times 10^{-19} \times 10}$$

$$= 1.02 \times 10^{12}\ \text{Bq}$$

neutron absorption rate = ...1.0×10^{12}...... Bq [3]