TOPIC 29 Radioactive Decay

1 A certain radioactive nuclide of mass number m_X disintegrates, with the emission of an electron and γ radiation only, to give a second nuclide of mass number m_Y. Which one of the following equations correctly relates m_X and m_Y?

A $m_Y = m_X - 4$
B $m_Y = m_X - 2$
C $m_Y = m_X - 1$
D $m_Y = m_X$
E $m_Y = m_X + 1$

N76/II/36

2 Which one of the following combinations of radioactive decay results in the formation of an isotope of the original nucleus?

A α and four β
B α and two β
C α and β
D two α and β
E four α and β

J77/II/35

3 Which one of the following statements is true of both α-particles and X-rays?

A They cause ionisation of the air when they pass through it.
B They can be detected after passing through a few millimetres of aluminium.
C They can be deflected by electric fields.
D They can be deflected by magnetic fields.
E They are used industrially for the photographic detection of flaws in metal castings.

N77/II/36; J84/II/36

4 A naturally occurring isotope of radium, ${}^{226}_{88}\text{Ra}$, has a half-life of 1622 years. Its radioactive decay may be represented by the equation

$${}^{226}_{88}\text{Ra} \rightarrow \text{X} + \alpha + \gamma.$$

where X is a daughter nuclide, α is an alpha-particle and γ is a gamma ray, the atomic number of X is

A 86 **B** 88 **C** 89 **D** 224 **E** 227

J78/II/35

5 The nucleus of uranium (${}^{238}_{92}\text{U}$) may undergo successive decays, emitting respectively an α-particle, a β-particle and a γ-photon. The resulting nucleus may be represented by

A ${}^{237}_{92}\text{U}$
B ${}^{234}_{91}\text{Pa}$
C ${}^{233}_{91}\text{Pa}$
D ${}^{232}_{91}\text{Pa}$
E ${}^{234}_{89}\text{Ac}$

N78/II/36

6 The isotope which decays by β-emission to produce ${}^{111}_{48}\text{Cd}$ is

A ${}^{111}_{47}\text{Ag}$
B ${}^{111}_{49}\text{In}$
C ${}^{110}_{47}\text{Ag}$
D ${}^{113}_{50}\text{Sn}$
E ${}^{112}_{47}\text{Ag}$

N79/II/34

7 The nuclide ${}^{226}_{88}\text{Ra}$ occurs in appreciable quantities in a mineral of great geological age despite the fact that its half-life is only a very small fraction of the age of the mineral. This is because

A the radioactive decay of ${}^{226}_{88}\text{Ra}$ is exponential and the activity can never become zero.
B ${}^{226}_{88}\text{Ra}$ is constantly being formed by the decay of a longer-lived isotope.
C the mineral is constantly being subjected to neutron bombardment from the centre of the Earth, forming more ${}^{226}_{88}\text{Ra}$.
D the concentration ${}^{226}_{88}\text{Ra}$ is constantly being re-generated by radioactive fall-out from the atmosphere.
E the rock surrounding the ${}^{226}_{88}\text{Ra}$ slows down the escape of the alpha-particles and gamma-rays.

N79/II/36; J82/II/38; J87/I/27

8 In order to trace the line of a water-pipe buried 0.4 m below the surface of a field, an engineer wishes to add a radioactive isotope to the water.

Which sort of isotope should be chosen?

	emitter	*half-life*
A	β	a few hours
B	β	several years
C	γ	a few hours
D	γ	several years

J80/II/33; J96/I/30

9 Fig. 1 represents a series of radioactive changes in which nuclide W forms nuclide *X* which then forms nuclide *Y* and finally nuclide Z.

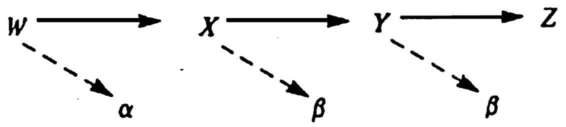


Fig. 1

Which one of the following gives the total change of mass number and of nuclear charge?

	Change of mass number from W to Z	*Change of nuclear charge from W to Z*
A	–2	+1
B	–2	0
C	–2	–1
D	–4	+1
E	–4	0

J81/II/34; N84/II/38

10 A head-on elastic collision between an α-particle and a stationary helium nucleus would be impossible to detect in a cloud chamber because

A no photons are emitted in the collision.

B the helium nucleus is too light to deflect the α-particle noticeably.

C the track of the helium nucleus after the collision is indistinguishable from that of the α-particle before the collision.

D details of the interactions of individual particles cannot be detected in a cloud chamber.

E uncharged particles do not leave tracks in a cloud chamber. J82/II/35

11 Bombardment of a certain material with α-particles produces an emission which penetrates lead, ejects protons from paraffin wax, and travels at speeds up to 5×10^7 ms^{-1}. What does this emission consist of?

A X-rays
B α-particles
C β-particles
D neutrons
E ultraviolet light

N82/II/36; J84/II/34

12 An event on a distant star causes the emission of a burst of radiation containing β-particles, γ rays and light. Which one of the following statements about the order in which these radiations arrive at the Earth is *correct*?

A The light would arrive first.

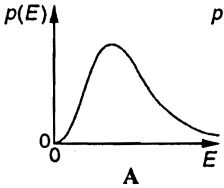
B The γ-rays would arrive first.

C The light and the γ-rays would arrive together, ahead of the β-particles.

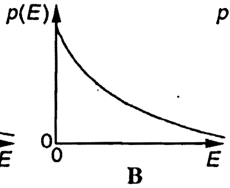
D The light and the β-particles would arrive together, ahead of the γ-rays.

E All three would arrive together. N82/II/37

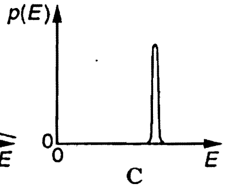
13 Which one of the following graphs could represent the distribution *p* (*E*) of energies *E* of α-particles emitted from a given source?



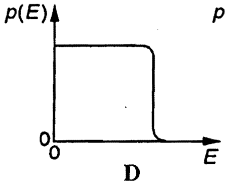
A



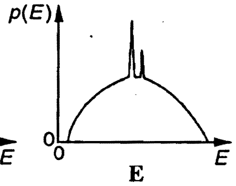
B



C



D



E

J83/II/36

14 Because of the random nature of the radioactive emission process, the count-rate recorded by a Geiger-Muller tube or solid-state detector from a supposedly constant source is subject to statistical fluctuations. For example, if the total count recorded from such a source in a given time is *N*, the variability of repeated measurements is of the order of $\sqrt{N}$. For how many counts should counting continue in order to obtain the mean count rate to a precision of about 1%?

A 100
B 1000
C 10 000
D 100 000
E 1 000 000

N83/II/35

15 Methods of recording electrical impulses from a Geiger-Müller tube include (i) an amplifier and loudspeaker, (ii) a counter (scaler), (iii) a ratemeter. Which one of the following statements is *correct*?

A The loudness of an individual click from the loudspeaker is a measure of the number of particles arriving per second.

B The pitch of the signal in the loudspeaker may be used to distinguish between the types of radiation producing the impulses.

C The reading on the counter is the instantaneous value of the number of electrical impulses per unit time.

D The reading on the ratemeter is the average value of the number of electrical impulses per unit time.

E For a counter and a ratemeter both connected to the same G-tube, the relation between the readings *c* and *r* of the counter and ratemeter respectively is $c = \mathrm{d}r/\mathrm{d}t$.

N83/II/36

16 When it disintegrates, a certain radioactive nuclide P emits γ-radiation and a single α-particle, forming a daughter product Q. Which one of the following statements is true?

A P and Q are isotopes of the same element.

B The mass number of P is one more than that of Q.

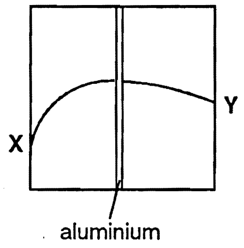
C The mass number of P is one less than that of Q.

D P has more protons in its nucleus than Q.

E The atomic number of P is less than that of Q.

N84/II/36

17 Radiation from a radioactive source enters an evacuated region in which there is a uniform magnetic field perpendicular to the plane of the diagram. This region is divided into two by a sheet of aluminium about 1 mm thick. The curved, horizontal path followed by the radiation is shown in the diagram below.



Which of the following correctly describes the type of radiation and its point of entry?

	type of radiation	*point of entry*
A	alpha	X
B	alpha	Y
C	beta	X
D	beta	Y
E	gamma	X

N87/I/27

18 As a result of successive decays in a radioactive series, the nucleon number (mass number) of an isotope decreases by 4 while its proton number (atomic number) is unchanged.

How many α-particles and β-particles are emitted?

	number of particles emitted	
	α	β
A	1	1
B	1	2
C	1	4
D	2	1
E	2	2

N92/I/28

19 The table shows some properties of five nuclear particles.

Which particle is a neutron?

particle	*affected by electric and magnetic fields*	*mass in terms of the proton mass m_p*
A	yes	$4m_p$
B	yes	0
C	yes	m_p
D	no	0
E	no	m_p

N92/I/29

20 ${}^{238}_{92}\mathrm{U}$ decays through a series of transformations to a final stable nuclide. The particles emitted in the successive transformations are

$$\alpha \quad \beta \quad \beta \quad \alpha \quad \alpha$$

Which nuclide is **not** produced during this series of transformations?

A ${}^{228}_{88}\mathrm{Ra}$

B ${}^{230}_{90}\mathrm{Th}$

C ${}^{234}_{91}\mathrm{Pa}$

D ${}^{234}_{92}\mathrm{U}$

J96/I/29

21 Part of the actinium radioactive series can be represented as follows:

$$\begin{tikzcd} {}^{211}_{83}\mathrm{Bi} \arrow[r, "\alpha,\ \gamma"] \arrow[dr, "\beta,\ \gamma"'] & \mathrm{T}l \arrow[r] & \mathrm{Pb} \\ & \mathrm{PO} \arrow[ur, "\alpha,\ \gamma"'] & \end{tikzcd}$$

The symbols above the arrows indicate the modes of decay.

(a) Write down the atomic numbers and mass numbers of T*l*, Po and Pb in this series.

(b) What is a possible mode of decay for the stage T*l* to Pb? N77/I/10

22 A certain α-particle track in a cloud chamber has a length of 37 mm. Given that the average energy required to produce an ion pair in air is 5.2×10^{-18} J and that α-particles in air produce on average 5.0×10^3 such pairs per mm of track, find the initial energy of the α-particle. Express your answer in MeV. N83/I/12

23 The nuclide ${}^{232}_{90}\mathrm{Th}$ decays to a final stable product, ${}^{208}_{82}\mathrm{Pb}$, through a series of radioactive nuclides. At each stage an alpha-particle or a beta-particle is emitted. Find the numbers of each type of particle emitted during the complete decay process. J86/II/6

24 The table below shows some properties of the ionising radiations alpha, beta and gamma. (*e* is the elementary charge, *c* is the speed of light and *u* is a unit of atomic mass.)

Complete the table.

	alpha	beta	gamma
charge	+2*e*		
mass		1/1840 *u*	
typical speed	0.1 *c*		
nature	particle		
penetrating ability		stopped by a few mm of aluminium	

[6] N91/II/5

25 A decay sequence for a radioactive atom of radon-219 to a stable lead-207 atom is as shown in Fig 2.

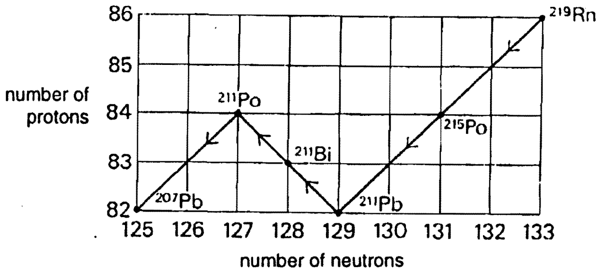


Fig. 2

(a) What do the numbers on the symbol ${}^{207}_{82}\mathrm{Pb}$ represent? [1]

(b) (i) Write down a nuclear equation representing the decay of ${}^{219}_{86}\mathrm{Rn}$ to ${}^{215}_{84}\mathrm{Po}$. [2]

(ii) Write down the name of the particle which is emitted in this decay. [1]

(c) (i) What particle is emitted when ${}^{211}_{83}\mathrm{Bi}$ decays?

(ii) What happens within the nucleus to cause this decay? [2]

J92/II/7 (part)

Long Questions

26 Figs. 3–5 are photographs of traces obtained in cloud chambers under certain conditions.

(a) Fig. 3 shows α-particle tracks. What conclusions can you draw from the fact that the traces are all nearly straight and of approximately the same length? Why are some of the particles deflected *near the ends* of their tracks? [4]

(*b*) Fig. 4 shows a track produced by a β-particle in a chamber in which a magnetic field was applied. The point of entry of the particle is marked by an arrow. Explain as many features of this track as you can.

An electron describes a circular path of radius 4.0 cm in a uniform magnetic field of flux density 3.0×10^{-3} T. Find the speed of the electron. [8]

[Charge of electron, $e = -1.6 \times 10^{-19}$ C; mass of electron, $m_e = 9.1 \times 10^{-31}$ kg.]

(*c*) Fig. 5 shows the result of the passage of γ-radiation through a chamber. Co-ordinate axes have been drawn at the edges of the photograph for reference purposes. Give the approximate co-ordinates of the points of entry and exit of the γ-radiation. Summarise the properties of γ-radiation and explain the appearance of the track. [8]

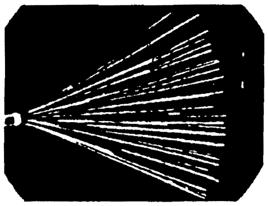


Fig. 3

Fig. 4

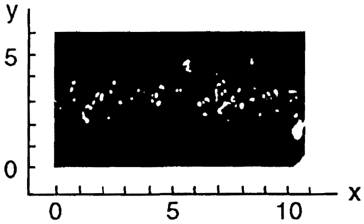


Fig. 5

N74/I/10

27 Explain what is meant by the terms in *italics* in the following statements:

^{238}U is an *alpha-emitter of half life* 4.5×10^9 years;

^{235}U is made to undergo *fission* by *thermal neutrons.*

Outline the process by which a nuclear chain reaction may be maintained in natural uranium. Summarise the factors that make such a reaction unlikely to take place in nature.

Assuming that each fission of a ^{235}U atom releases 3×10^{-11} J of energy and eventually results in the formation of one ^{239}Pu atom, calculate to the nearest month how long a reactor of total output 100 MW would take to produce 10 kg of plutonium.

[The Avogadro constant = 6×10^{23} mol^{-1}, 1 month = 2.6×10^6 s.] J77/III/6

28 Give a summary of the changes that occur within atoms when they emit (*a*) α-, (*b*) β-, (*c*) γ-radiation.

One gram of radium emits 1.4×10^{11} α-particles each second. In the course of a year, these particles form 0.16 cm^3 of helium gas, measured at s.t.p. Use these data to estimate the number of helium atoms in one gram of helium. Show whether your result is consistent with the known value of the Avogadro constant.

[Density of helium at s.t.p. = 0. 18 kg m^{-3},
The Avogadro constant = 6.0×10^{23} mol^{-1},
1 year = 3.2×10^7 s.] N80/III/6 (part)

29 (*a*) Describe the principles of an experiment which could be performed in a school laboratory to determine the speed of the electrons in a beam travelling through a vacuum. Give the theory which would enable you to calculate the speed. [8]

(*b*) In a particle detector such as a cloud chamber, sub-nuclear particles leave tracks which can be photographed. One such photograph in sketched in Fig. 6. The sketch shows a series of events started by the particle responsible for track **A**. Tracks **D** and **E** were not visible in the original photograph but have been added to the sketch. Such tracks are alway straight. Other tracks are curved due to a uniform magnetic field acting at right angles to the plane of the sketch. All the tracks are in the plane of the sketch.

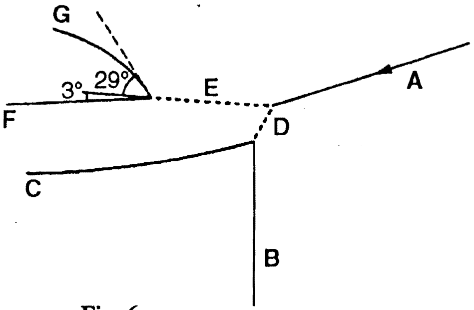


Fig. 6

State and explain what can be deduced from each of the following observations:

(i) Tracks **D** and **E** are straight and not visible.

(ii) Tracks **C** and **G** curve in opposite directions.

(iii) The curvature of track **G** is greater than that of track **C**.

(iv) Track **B** appears to be straight even though charge must be conserved at the intersection of tracks **B**, **C** and **D**. [8]

(*c*) The particle responsible for track **F** in Fig. 6 was a proton travelling at 3.5×10^7 m s^{-1} at an angle of 3.0° to the direction of track **E**. You may also assume that the particle responsible for track **G** had an initial velocity of 2.4×10^7 m s^{-1} in a direction making an angle of 29° to the direction of **E**.

Calculate the mass of the particle responsible for track **G** and comment on the result you obtain. [6]

J89/II/11

30 *(a)* Naturally occurring radioactivity results in the emission of three types of ionising radiation — alpha, beta and gamma.

Distinguish between the three types in terms of their relative charges, masses and speeds. [6]

(b) In the early years of this century Mdm Curie drew an illustration similar to Fig. 7 which indicated how the three radiations travelled in air in a uniform magnetic field. The illustration and Fig. 7 were not drawn to scale.

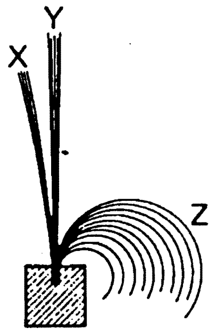


Fig. 7

(i) Identify the radiations **X**, **Y** and **Z**.

(ii) What is shown by the fact that the lines for **X** all have approximately the same length?

(iii) What is shown by the fact that the lines for **Z** have different curvatures?

(iv) In what direction does the magnetic field exist? [5]

(c) One particle of radiation **Z** has a mass of 9.1×10^{-31} kg, a velocity of 4.8×10^{7} m s^{-1} and a charge of -1.60×10^{-19} C. Find the radius of curvature of its circular path in a uniform magnetic field of flux density 0.32 T. [4]

(d) By reference to information you have given in *(a)* estimate the radius of curvature of the path of a particle of radiation **X** in this magnetic field. [3]

(e) Give two reasons why it is difficult, if not impossible, to take a photograph which is like Fig. 7. [2]

J91/III/6

31 *(a)* Compare the properties of a photoelectron and a β-particle by making reference to

(i) the origin,

(ii) the process of emission,

(iii) the energy of the particles. [6]

N95/III/6 (part)

32 *(a)* Explain what is meant by

(i) the *radioactive decay* of a nucleus,

(ii) *nuclear fission.* [4]

N97/III/6 (part)

Law of Decay

33 The rate of decay, dN/dt, of the number, N, of nuclei present in a sample of a radioactive element at time t

A is proportional to t.
B is proportional to N.
C is proportional to $1/t$.
D is proportional to $1/N$.
E is constant and equal to λ, the decay constant. J77/II/36

34 The ^{14}C : ^{12}C ratio of living material has a constant value during life but the ratio decreases after death because the ^{14}C is not replaced. The half-life of ^{14}C is 5600 years.

The ^{14}C content of a 5 g sample of living wood has a radioactive count rate of about 100 per minute. If the count rate of a 10 g sample of ancient wood is 50 per minute, the age of the sample is about

A 1400 years
B 2800 years
C 5600 years
D 11200 years
E 22400 years

N77/II/35

35 The graph below (Fig. 8) shows the number of particles N_t emitted per second by a radioactive source as a function of time t.

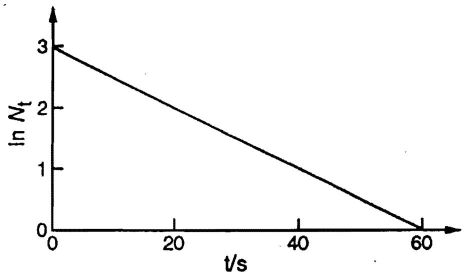


Fig. 8

The relationship between N_t and t is

A $N_t = 1000\,e^{-(20t/s)}$
B $N_t = 20\,e^{(20t/s)}$
C $N_t = 3\,e^{-(0.05t/s)}$
D $N_t = 20\,e^{-(0.05t/s)}$
E $N_t = 1000\,e^{(0.05t/s)}$

[$\ln 20 = 3.00$] J80/II/19

36 The equations

$$\frac{dN}{dt} = -\lambda N \quad \text{and} \quad N = N_0 e^{-\lambda t}$$

describe how the number N of undecayed atoms in a sample of radioactive material, which initially (at t = 0) contained N_0 undecayed atoms, varies with time t.

Which one of the following statements about λ is *correct*?

A $\lambda \delta t$ gives the fraction of atoms present which will decay in the next small time interval δt.
B λ is the time needed for N to fall from N_0 to the value N_0/e.
C λ is equal to the half-life of the sample.
D λ is the number of atoms left after a time equal to e seconds.
E λ is the chance that any one atom will still be undecayed after one second. J81/II/35

37 The half-life of a certain radioactive element is such that $\frac{7}{8}$ of a given quantity decays in 12 days.

What fraction remains undecayed after 24 days?

A 0 **B** $\frac{1}{128}$ **C** $\frac{1}{64}$ **D** $\frac{1}{32}$ **E** $\frac{1}{16}$

N81/I/28

38 The activity from a radioactive source is found to fall by 0.875 of its initial activity in 210 s. What is the half-life of the source?

A 30 s **D** 105 s
B 60 s **E** 120 s
C 70 s

J82/II/36

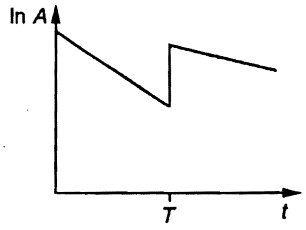
39 What is the relationship between the decay constant λ and the half-life $t_{1/2}$ of a radioactive isotope?

A $\lambda = t_{1/2}$ **D** $\lambda = (\ln 2)/t_{1/2}$
B $\lambda = 1/t_{1/2}$ **E** $\lambda = \frac{1}{t_{1/2} \ln 2}$
C $\lambda = t_{1/2} \ln 2$

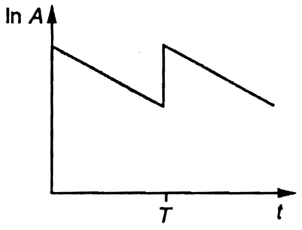
J84/II/35

40 At time $t = 0$ some radioactive gas is injected into a sealed vessel. At time T some more of the same gas is injected into the same vessel.

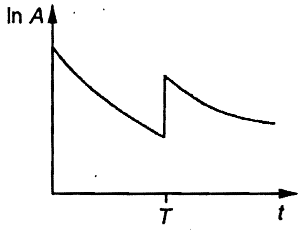
Which one of the following graphs best represents the variation of the logarithm of the activity A of the gas with time t?



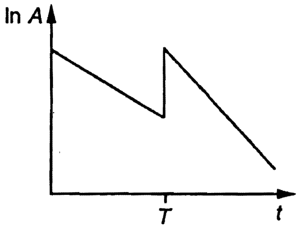
A



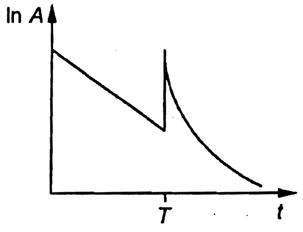
B



C



D



E

N85/I/27

41 The radioactive decay of a certain nuclide is governed by the following relationship:

$$\frac{dn}{dt} = -\lambda n \text{ where } \lambda = 2.4 \times 10^{-8}\ \text{s}^{-1}$$

What is the half-life of the nuclide?

A 2.9×10^{7} s **D** 3.4×10^{-8} s
B 1.3×10^{7} s **E** 8.0×10^{-8} s
C 1.2×10^{-8} s

N86/I/27

42 The half-life of a certain radioactive isotope is 32 hours. What fraction of a sample would remain after 16 hours?

A 0.25 **D** 0.71
B 0.29 **E** 0.75
C 0.50

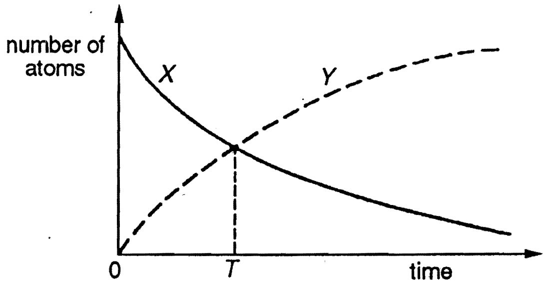
J89/I/28

43 A radioactive source consists of 6.4×10^{11} atoms of a nuclide of half-life 2 days. A second source consists of 8×10^{10} atoms of another nuclide of half-life 3 days. After how many days will the numbers of active atoms in the two sources be equal?

A 6 **B** 9 **C** 12 **D** 15 **E** 18

J90/I/30

44 The graph represents the decay of a newly-prepared sample of radioactive nuclide X to a stable nuclide Y. The half-life of X is τ. The growth curve for Y intersects the decay curve for X after time T.



What is the time T?

A τ/2 **D** ln (2τ)
B ln (τ/2) **E** 2τ
C τ

N90/I/30

45 Radioactive ^{14}C dating was used to find the age of a wooden archaeological specimen. Measurements were taken in three situations for which the following count rates were obtained:

specimen	*count rate*
1 g sample of living wood	80 counts per minute
1 g sample of archaeological specimen	35 counts per minute
no sample	20 counts per minute

If the half-life of ^{14}C is known to be 5700 years, what was the approximate age of the archaeological specimen?

A 2500 years **C** 11 000 years
D 13 000 years **E** 23 000 years
B 7000 years

J91/I/30

46 In a cancer therapy unit, patients are given treatment from a certain radioactive source. This source has a half-life of 4 years. A particular treatment requires 10 minutes of irradiation when the source is first used.

How much time is required for this treatment, using the same source, 2 years later?

A 7 minutes
B 10 minutes
C 14 minutes
D 20 minutes

N91/I/30; J95/I/30

47 The table shows the count-rate recorded at a point in a laboratory at various times, with and without a source in position.

time/days	*count-rate*/s^{-1}	
	with source	*without source*
10	60	20
30	30	20
90	20	20

From these readings, what is the half-life of the source?

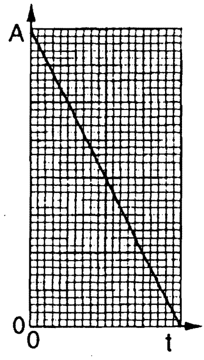
A 10 days
B 15 days
C 20 days
D 30 days
E 50 days

N92/I/30

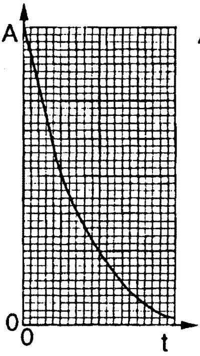
48 A radioactive isotope decays by a one-stage process into a stable nuclide.

Which graph could represent the activity A of the isotope plotted against time t?

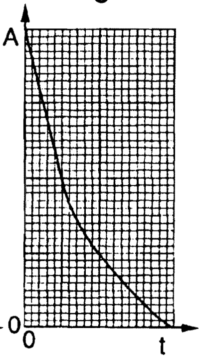
A



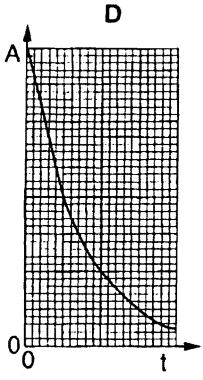
B



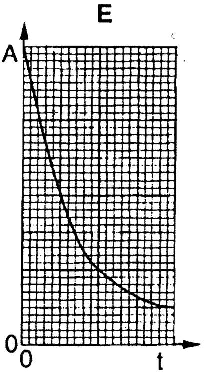
C



D



E



J93/I/30

49 A radioactive isotope has a decay constant λ and a molar mass M.

Taking the Avogadro constant to be L, what is the activity of a sample of mass m of this isotope?

A λmML **B** $\dfrac{\lambda mL}{M}$ **C** $\dfrac{\lambda ML}{m}$ **D** $\dfrac{mL}{\lambda M}$ **E** $\dfrac{m\lambda}{ML}$

N93/I/29

50 A radioactive source contains the nuclide $^{187}_{74}\mathrm{W}$ which has a half-life of 24 hours.

In the absence of this source, a constant average count-rate of 10 s^{-1} is recorded.

Immediately after the source is placed in a fixed position near the counter, the average count-rate rises to 90 s^{-1}.

What average count-rate is expected with the source still in place 24 hours later?

A 30 s^{-1} **B** 40 s^{-1} **C** 45 s^{-1} **D** 50 s^{-1}

J94/I/30

51 Samples of two radioactive nuclides, **X** and **Y**, each have equal activity A_0 at time $t = 0$. **X** has a half-life of 24 years and **Y** a half-life of 16 years.

The samples are mixed together.

What will be the total activity of the mixture at $t = 48$ years?

A $\frac{1}{12}A_0$ **B** $\frac{3}{16}A_0$ **C** $\frac{1}{4}A_0$ **D** $\frac{3}{8}A_0$

N94/I/30

52 A newly prepared radioactive nuclide has a decay constant λ of 10^{-6} s^{-1}.

What is the approximate half-life of the nuclide?

A 1 hour
B 1 day
C 1 week
D 1 month

J97/I/30

53 A source contains initially N_0 nuclei of a radioactive nuclide.

How many of these nuclei have decayed after a time interval of three half-lives?

A $\dfrac{N_0}{8}$ **B** $\dfrac{N_0}{3}$ **C** $\dfrac{2N_0}{3}$ **D** $\dfrac{7N_0}{8}$

J98/I/30

54 The following information concerns a sample of a certain radioisotope:

the activity at time zero is A_0;
the activity at time t is A ;
the number of undecayed nuclei at time t is N ;
the decay constant is λ;
the half-life is $t_{1/2}$.

Which relationship is **not** correct ?

A $A = A_0 \exp(-\lambda t)$
B $A = \lambda N$
C $A \doteq t_{1/2} N$
D $N = 1.44\, t_{1/2} A$

N98/I/30

55 The initial activity of a sample of a radioactive isotope containing N_0 nuclei is A_0.

What is the number of unchanged nuclei when the activity has declined to $\frac{A_0}{2}$?

A $0.69N_0$ **B** $\frac{0.69\,N_0}{2}$ **C** $\frac{N_0}{2}$ **D** $\frac{N_0}{1.38}$

N99/I/30

56 A radioactive source produces 10^6 α-particles per second. When all the ions produced in air by these α-particles are collected, the ionisation current is about 0.01 μA.

If the charge on an ion is about 10^{-19} C, what is the best estimate of the average number of ions produced by each α-particle?

A 10^5 **B** 10^6 **C** 10^7 **D** 10^8

J2000/I/30

57 Which of the following defines the decay constant λ of a radioactive nuclide?

A $\frac{\text{activity}}{\text{number of undecayed nuclei}}$

B $\frac{\text{half-life}}{0.693}$

C the number of nuclei that decay per unit time

D the time for the activity of the nuclide to be reduced by a factor of 2.

N2000/I/30

58 *(a)* Write down the equation which relates the rate of decay $-\mathrm{d}n/\mathrm{d}t$ in a sample of n radioactive nuclei to their decay constant λ. What are the dimensions (or units) of λ?

(b) Initially, a sample contains 1.0×10^6 radioactive nuclei of half-life t. About how many will remain after a time $0.5\,t$?

N81/I/11

59 A particular medical application requires a radioactive source with an activity of 3.90×10^3 Bq at the start of the treatment. The nuclide selected has a half-life of 1.80×10^5 s and is prepared at a Radio-isotope Centre 1 week (6.05×10^5 s) before the treatment is due to commence. What should be the activity of the source at the time of preparation?

[1 Bq = 1 disintegration per second.]

N84/I/11

60 ${}^{32}_{15}\mathrm{P}$ is a beta-emitter with a decay constant of 5.6×10^{-7} s^{-1}. For a particular application the initial rate of disintegration must yield 4.0×10^7 beta particles every second. What mass of pure ${}^{32}_{15}\mathrm{P}$ will give this decay rate?

J85/II/7

61 An alpha-emitting radioactive source, placed inside an ionisation chamber, produces an ionisation current of 2.4×10^{-6} A. If each alpha particle produces, on average, 2.0×10^5 ion pairs, find the activity of the source. (Assume that the ions are singly-charged and that all are collected.)

N85/II/6

62 An experiment is carried out in which the count rate is measured at a fixed distance from a sample of a certain radioactive material. Fig. 9 shows the variation of count rate with time that was obtained.

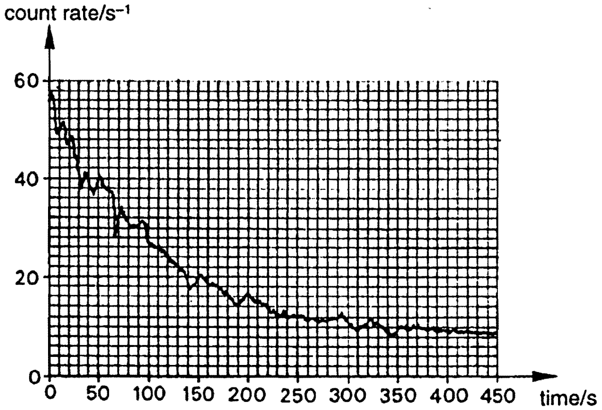


Fig. 9

Use the graph to estimate the half-life of the material.

Explain how you dealt with the problems of *(a)* the random nature of the count rate, *(b)* the background radiation. [8]

N91/II/7

63 *(d)* The half-life of ${}^{219}_{86}\mathrm{Rn}$ is 4.0s. At time t = 20 s, what fraction of the radon atoms present at time t = 0, will be undecayed? [2] J92/II/7 (part)

64 In a radioactive decay, the number n of atoms undecayed at time t is given by

$$n = n_0 \exp(-\lambda t),$$

where n_0 is the number of atoms present at the start of the decay and λ is the decay constant.

(a) Sketch, on the axes in Fig. 10, a graph which shows qualitatively how the number of undecayed atoms varies with time.

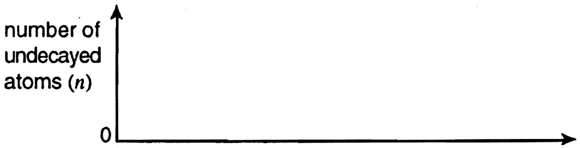


Fig. 10 [1]

(b) For a particular radioactive source, $\lambda = 1.83 \times 10^{-9}$ s^{-1} and $n_0 = 3.72 \times 10^{21}$.

(i) Calculate the number of undecayed atoms when $t = 3.16 \times 10^7$ s (1 year). [2]

(ii) Calculate the half-life of the source. [3]

(iii) Calculate the activity of the source at the start of the decay (t = 0). [2]

N93/II/7

65 *(a)* What is meant by

(i) the *decay* constant λ of a radioactive material,

(ii) the *half-life* $t_{1/2}$? [2]

(b) The decay constant and the half-life are related by the equation

$$\lambda = \frac{0.693}{t_{1/2}}.$$

The half-life of $^{60}_{27}$Co is 5.26 years.

(i) What do the numbers 27 and 60 represent? [2]

(ii) Calculate the decay constant of $^{60}_{27}$Co. [1]

(iii) Calculate the activity of 1.00 gram of $^{60}_{27}$Co. [3]

(60 grams of $^{60}_{27}$Co contain 6.02×10^{23} atoms.)

J94/II/7

66 A student stated that 'radioactive materials with a short half-life always have a high activity'.

(a) What is meant by

(i) *half-life*,

(ii) *activity*? [3]

(b) Discuss whether the student's statement is valid. [3]

N94/II/6

67 The activity of a piece of radioactive material is 4.3×10^5 Bq at time $t = 0$. The number of undecayed atoms in the material at time $t = 0$ is 7.9×10^{15}. Calculate

(a) (i) the activity after 4.0 half-lives have elapsed,

(ii) the number of undecayed atoms after 4.0 half-lives, [4]

(b) the decay constant λ, [3]

(c) the half-life $t_{1/2}$. [2]

N95/II/7

68 *(a)* Distinguish between the *count-rate* as measured by a detector, and the *activity* of a source.

count-rate: ....

activity: .... [2]

(b) A radioactive source of activity 3.7×10^{10} Bq emits γ-ray photons uniformly in all directions. In order to shield the source, it is placed at the centre of a hollow lead sphere, as shown in Fig. 11.

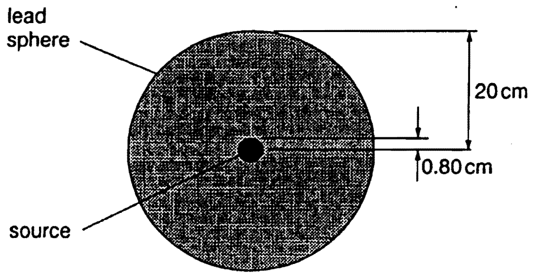


Fig. 11

The inner and outer radii of the sphere are 0.80 cm and 20 cm respectively.

Lead absorbs γ-ray photons such that, for every 1.2 cm thickness of lead through which photons pass, half the total number of photons entering that thickness of lead are absorbed.

(i) Show that the fraction of the total number of photons emitted by the source which emerge from the lead sphere is

$$\frac{1}{65536}.$$

(ii) Hence calculate the count-rate per unit area at the surface of the sphere. [5]

(c) The absorption of the γ-ray photons produces a heating effect in the lead. Suggest, with a reason, which region of the sphere is likely to experience the greatest heating effect due to the absorption of γ-ray photons. [2]

N96/II/7

69 *(a)* What is meant by the *random* nature of radioactive decay? [1]

(b) The thickness of a sheet of aluminium foil is to be monitored using β-radiation as illustrated in Fig. 12.

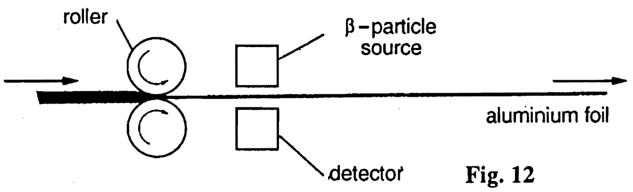


Fig. 12

The separation of the rollers is controlled by the output from the detector with the intention of maintaining a constant foil thickness.

(i) State what would happen to the separation of the rollers if the output from the detector were to increase.

(ii) Suggest why a γ-radiation source would not be satisfactory for monitoring changes in thickness of the foil.

(iii) A β-particle source of half-life 14 days is installed in the monitor and then used for a working day of 8.0 hours.

1. Calculate the ratio

$$\frac{\text{activity of source at end of working day}}{\text{activity of source at start of working day}}$$

ratio = ...

2. Estimate the percentage change in foil thickness during one working day if no allowance is made for radioactive decay. State whether the change is an increase or a decrease.

change.. % [7]

J97/II/8

70 One isotope of potassium, ${}^{40}_{19}K$, has a half-life of 1.4×10^9 years and decays to form argon, ${}^{40}_{18}Ar$, which is stable. A sample of rock taken from the Sea of Tranquillity on the Moon contains both potassium and argon in the ratio

$$\frac{\text{number of Potassium-40 atoms}}{\text{number of Argon-40 atoms}} = \frac{1}{7}.$$

(a) Define *half-life*. [2]

(b) The decaying potassium nucleus emits a particle X.

(i) Write down the nuclear equation representing this decay.

(ii) Suggest the identity of X. [2]

(c) Assume that when the rock was formed, there was no Argon-40 present in the sample and that none has escaped subsequently.

(i) Estimate the age of the rock.

age = ... years

(ii) State, with a reason, whether your answer in (i) is an overestimate or an underestimate of the age of the rock if some escape of argon has occurred. [5]

N99/II/7

Long Questions

71 Define *half-life* and *decay constant* for a radioactive substance. State the relationship between them.

Outline an experiment to determine the half-life of a radioactive gas (such as radon) that has a half-life of about 1 min. Explain how the half-life is obtained from the readings.

The sodium atom ${}^{24}_{11}Na$ is radioactive. It can be produced at a constant rate K from the stable isotope ${}^{23}Na$ placed in a nuclear reactor. Construct an equation relating δN, the small increase in the number of ${}^{24}Na$ atoms, in time δt to λ, the decay constant of ${}^{24}Na$, and K, the rate of production of ${}^{24}Na$.

Hence show that the number of ${}^{24}Na$ atoms present in the reactor will eventually tend to a constant value. J78/III/6

72 *(a)* What do you understand by *half-life* $T_{1/2}$, and *decay constant* λ, for a radioactive substance? Deduce the relationship between them.

(b) (i) The first part of the decay series of the artificially produced neptunium isotope ${}^{237}_{93}Np$ involves the following sequence of emissions: $\alpha\ \beta\ \alpha\ \alpha\ \beta\ \alpha$. Illustrate these changes on a plot of N, the number of neutrons in the nucleus, against Z, the atomic number. Using the table of elements below, identify (by its symbol) the last element in this portion of the decay series, and make clear which isotope of this element is produced.

Element	Bi	Po	At	Rn	Fr	Ra	Ac	Th	Pa	U
Atomic number	83	84	85	86	87	88	89	90	91	92

(ii) Three other nuclides also initiate decay series. The half lives and abundances are as shown below.

Element	Half life/year	Natural abundance
${}^{232}Th$	1.4×10^{10}	abundant
${}^{235}U$	7.1×10^{8}	rather rare
${}^{237}Np$	2.2×10^{6}	not found
${}^{238}U$	4.5×10^{9}	abundant

Comment on the age of the Earth in the light of these data. J79/III/6

73 Uranium-238 is an *alpha-emitier* of *half-life* 4.5×10^9 years. Uranium-239 is *fissionable* by *thermal neutrons*. Explain the terms in italics. Explain also what is meant by *decay constant* and calculate its value for uranium-238.

A certain coal-fired power station burns 80 megatonnes of coal a year. The coal contains a 0.0002% impurity of uranium-238 of which 10% is discharged into the atmosphere as dust during combustion. Assuming that, on average, the dust takes one year to fall to earth, calculate the mass of uranium-238 in the air at any one time and the number of alpha-particles produced each second from this source.

Alpha-particle can be stopped by tissue paper. Discuss whether this implies that alpha-emitters present no health hazard in a school laboratory.

[1 year = 3.15×10^7 s; ln 2 = 0.693; 1 megatonne = 1×10^9 kg.]

J81/III/6

74 Radioactivity is often said to be a random process. What is the meaning of the word *random* in this context?

Write down the equation for the activity of a pure radioactive source in terms of the number of radioactive nuclei present. Show how this is consistent with the random nature of the process. Hence define *decay constant. Define half-life* and show how the half-life is related to the decay constant.

A recent theory suggests that the proton may be unstable with a half-life of the order of 10^{34} years. How many of the 3×10^{33} protons in a swimming bath would you expect to decay in 5 years?

After such decays, γ-rays of wavelength 2.4×10^{-12} m would be expected. Calculate the ratio of the mass of such a γ-ray photon to the rest mass of an electron. N82/III/6

75 What do you understand by α, β and γ radiation? When an isotope of boron ${}^{10}_{5}B$ is irradiated by slow neutrons, two reactions may take place. In each reaction, an α particle and another nucleus are produced but, in one, the total kinetic energy of the particles after the reaction is 2.31 MeV and a γ ray is observed whereas, in the other, the energy is

2.79 MeV and no γ ray is emitted. Write down nuclear equations to represent these reactions, identify the other nucleus formed and calculate the frequency of the γ ray.

Living material contains a fairly constant small fraction of a radioactive isotope ^{14}C. After death, the activity from the ^{14}C present in the material decays with a half-life of 5.7×10^3 years. A certain quantity of carbon converted from recently dead organic matter to carbon dioxide and placed in a GM tube gave 12 counts per minute above background. If the same quantity of carbon were taken from a linen shroud and similarly treated, what count rate would you expect if the shroud were

(c) a relic dating from the early Christian era, about A.D. 33,

(d) a medieval forgery dating from about A.D. 1100?

N83/III/6 (part)

76 Explain the meaning of the words in *italics* in the following statement. The nuclide $^{90}_{38}$Sr is a β-*emitter* of *half-life* 28 years but the nuclide $^{238}_{94}$Pu emits two groups of α-*particles* which differ in energy by 0.045 MeV. Explain the significance of the symbols in $^{238}_{94}$Pu.

Express the energy difference in joules and calculate the mass of this energy.

Discuss how mass is conserved in the two types of plutonium (Pu) disintegration, despite there being this difference in the energies of the α-particles produced.

If a ^{90}Sr source emits many β-particles in one second today, how long will it take to emit the same number of β-particles in the year 2040 A.D.?

In what year will the source take the whole year to emit the same number of β-particles as it emits in one second today?

J84/III/6

77 The decay of radioactive nuclei is said to be a *random phenomenon.* What does *random* mean in this context? How does the rate of decay R at a given instant depend on the number N of radioactive nuclei present at that instant? (Assume N to be large.)

A certain beta-emitter has a half-life of approximately one hour. Describe an experiment to measure this half-life, and show how the result would be obtained from the readings you had taken.

A student performs this experiment and measures the half-life as 3300 ± 200 s. When readings are completed, the activity is 7.4×10^5 Bq. Safety regulations permit such emitters to be disposed with domestic waste provided that the activity is 3.7×10^4 Bq or less. Find the minimum time T after the end of the experiment for which the source should be retained before disposal.

[1 Bq (1 becquerel) represents an activity of 1 disintegration per second.]

J86/II/11

78 Explain the principle of operation of any device suitable for the detection of alpha-radiation. [4]

The equation

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + \alpha$$

represents the decay, by alpha-emission, of a uranium nucleus. Show how atomic number and mass number are conserved in this decay. Give a qualitative explanation of how energy and mass are conserved. [5]

Explain what is meant by the *decay constant* λ and the *half-life* $t_{1/2}$ of a radioactive substance, and show that these quantities are connected by the relation $\lambda = 0.693/t_{1/2}$. [3]

The half-life of $^{238}_{92}$U is 1.42×10^{19} s. What mass of this nuclide would give an emission of one alpha-particle per second? [5]

N87/II/12

79 The table below gives the activities measured over a period of 15 days of two separate radioactive sources, A and B, made from different nuclides.

Time / day	Activities/Bq	
	A	B
0	10 428	76 300
1	9 135	44 490
2	7 996	25 940
3	7 010	15 120
4	6 132	8 815
5	5 372	5 140
6	4 706	3 000
7	4 128	1 747
8	3 613	1 018
9	3 163	594
10	2 770	346
11	2 423	203
12	2 126	120
13	1 860	67
14	1 630	40
15	1 431	20

[1 Bq = 1 becquerel = 1 disintegration per second]

(a) Without plotting a graph, deduce the half-life of B. [3]

(b) Why is it necessary to ensure that the readings are taken at the same time each day? [1]

(c) Explain what is meant by the term *decay constant.* State the equation relating it to the half-life and find the value of the decay constant for source B. [4]

(d) Explain how you could still find the half-life of each of the nuclides if, instead of being separate, they had been thoroughly mixed with one another to form a composite source so that the only readings which could have been taken would have been the sum of the activities of A and B. [6]

(e) Comment on the accuracy with which the half-lives of A and B can be calculated from the data given. [2]

(f) Criticise the following statements.

(i) "After 14 days, the activity of B is 40 Bq: after 15 days, the activity is 20 Bq. The half-life of B is therefore 1 day." [3]

(ii) "Since A and B together go from 7706 Bq on day 6 to 1927 Bq on day 13, 2 half-lives of A and B together appear to be 7 days so the half-life of the composite source is 3.5 days." [3]

J88/II/11

80 *(a)* Describe the principle of operation of a solid-state detector of ionising radiation in terms of the generation and detection of charge carriers. [5]

(b) Explain how, when making measurements of radioactivity, practical steps can be taken to overcome problems caused by

(i) the random nature of radioactivity,

(ii) background radiation levels. [6]

(c) Radioactive iron, ^{59}Fe, is a radioactive nuclide with a half-life of 46 days. It is used medically in the diagnosis of blood disorders. Measurements are complicated by the fact that iron is excreted, i.e. removed, from the body at a rate such that 69 days after administering a dose, half of the iron atoms in the dose have been excreted. That is to say, iron has a biological half-life of 69 days.

(i) If the count rate from a blood sample is 960 counts per minute, what will it be from a similar blood sample taken 138 days later! [4]

(ii) How long after the first sample was taken would a further similar sample give a count rate of 480 counts per minute? [4]

(iii) Derive the relation between
T, the effective half-life of the radioactive nuclide in the body,
T_b, the biological half-life, and
T_r, the radioactive half-life. [3] N88/II/12

81 The table shows how C, the count rate measured in a sample of radioactive gas, varies with t, the time.

Time t /s	Count rate C /s^{-1}	Time t /s	Count rate C /s^{-1}
0	86.1	180	9.8
20	67.8	200	8.3
40	52.9	400	3.6
60	45.2	600	2.4
80	33.2	800	2.2
100	24.1	1000	2.6
120	20.1	1200	2.3
140	17.8	1400	2.5
160	13.7		

(a) Describe an experimental procedure by which such measurements could be obtained. [5]

(b) Use the data provided to tabulate R, the count rate due to the radioactive gas alone. [4]

(c) (i) Plot a graph of ln(C/s^{-1}) against t/s.

(ii) Deduce the decay constant and the half-life of the radioactive gas.

(iii) Explain why a graphical method is appropriate to handle the data and why a logarithmic graph is used in this case. [11]

(d) The gas considered in this question is present in many houses at a constant concentration. How is this possible when the gas has such a short half-life? [2]

N89/II/13

82 *(a)* Distinguish between α-particles, β-particles, γ-ray photons, making reference, wherever appropriate, to charge, mass, speed and penetration. [6]

(b) A radioactive isotope of thallium, ^{207}Th, is known to emit β-particles. It is suspected that the isotope also emits γ-radiation. You have available a ^{207}Th source with an activity of approximately 10^5 Bq. Devise an experiment, based on the different penetrating properties of β-particles and γ-ray photons, which could be used to confirm the emission of γ-radiation. [7]

(c) (i) Explain the meaning of the term *radioactive decay constant.*

(ii) ^{40}K, an isotope of potassium, has a half-life of 1.37×10^9 years and decays to an isotope of argon which is stable. In a particular sample of Moonrock; the ratio of potassium atoms to argon atoms was found to be 1:7. Estimate the age of the rock, assuming that originally there was no argon present.

(iii) State one other assumption which you have made in your calculation. [7]

J90/III/5

83 *(b)* A rolling mill produces sheet aluminium, the thickness of which must be kept within certain limits. In order to achieve this, the thickness of the sheet is monitored as it leaves the final set of rollers. The monitor consists of a β-particle source and a detector placed as shown in Fig. 13.

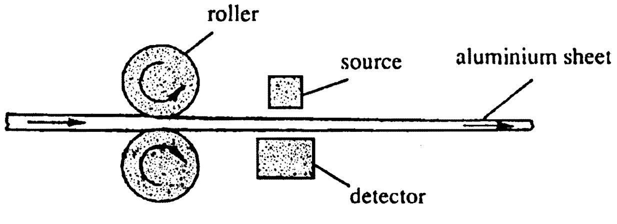


Fig. 13

(i) Discuss the advisability, or otherwise, of using a β-emitting source which has

(1) a high activity, giving a count rate many times that of background,

(2) a short half-life. [6]

(ii) For sheets of aluminium about 1 mm thick, the β-particle count rate C /s^{-1} is known to vary with thickness x / mm according to the expression

$$C = C_0 e^{-0.62x},$$

where C_0/s^{-1} is the count rate when $x = 0$.

Calculate the ratio

$$\frac{\text{maximum count rate}}{\text{minimum count rate}}$$

when $x = 1.00$ mm and x varies by ± 5.0%. [5]
J92/III/6 (part)

84 *(a)* State the changes to the number of protons and of neutrons that occur within nuclei when they emit

(i) α-particles,

(ii) β-particles,

(iii) γ-radiation. [5]

(b) A sample of radioactive material emits a narrow parallel beam of α-particles, β-particles and γ-radiation as illustrated in Fig. 14.

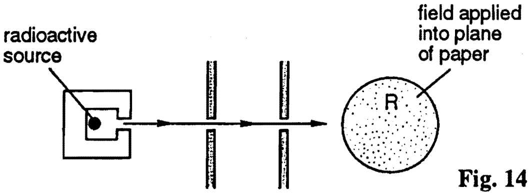


Fig. 14

The beam passes through a region R where a uniform field may be applied at right angles to the beam and into the plane of the paper. Discuss the effect on the beam if the field in the region R is

(i) an electric field,

(ii) a magnetic field. [8] N93/III/6 (part)

85 *(a)* Distinguish between the *radioactive decay* and the *fission* of a nucleus. [5]

(b) (i) A radioactive source of activity A emits γ-ray photons uniformly in all directions. A detector, of effective area of detection S, is situated a distance x from the source, as shown in Fig. 15.

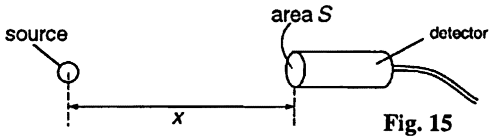


Fig. 15

Show that the number N of photons entering the detector per unit time is given by

$$N = \frac{SA}{4\pi x^2}$$

State any assumption you make in your derivation.

(ii) A γ-ray source is to be transported in a sealed wooden box.

The source is placed in a lead container which is surrounded by expanded polystyrene, as shown in Fig. 16.

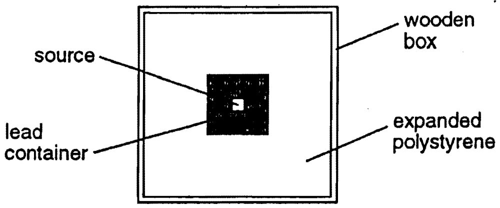


Fig. 16

Suggest why, on health grounds,

1. the source is placed in a *lead* container,
2. the lead container is surrounded by polystyrene. [7]

(c) The isotope Iron-59 is a β-emitter with a half-life of 45 days. In order to estimate engine wear, an engine component is manufactured from non-radioactive iron throughout which the isotope Iron-59 has been uniformly distributed. The mass of the component is 2.4 kg and its initial activity is 8.5×10^7 Bq.

The component is installed in the engine 60 days after manufacture of the component, and then the engine is tested for 30 days. During the testing period, any metal worn off the component is retained in the surrounding oil. Immediately after the test, the oil is found to have a total activity of 880 Bq. Calculate

(i) the decay constant for the isotope Iron-59,

(ii) the total activity of the component when it was installed,

(iii) the mass of iron worn off the component during the test. [8] J96/III/6

86 *(b)* Radon-220 ($^{220}_{86}$Rn) decays spontaneously with a half-life of 56 s to form polonium (Po). During this decay, an α-particle and a γ-ray photon are emitted with energies of 6.29 MeV and 0.55 MeV respectively.

(i) Write down a nuclear equation to represent the decay of a Radon-220 nucleus. [2]

(ii) Define what is meant by *half-life.* [2]

(iii) Calculate, for this decay,

1. the mass equivalence of the energy released during the decay,
2. the wavelength of the emitted γ-ray photon.

[5]
J2000/III/6 (part)