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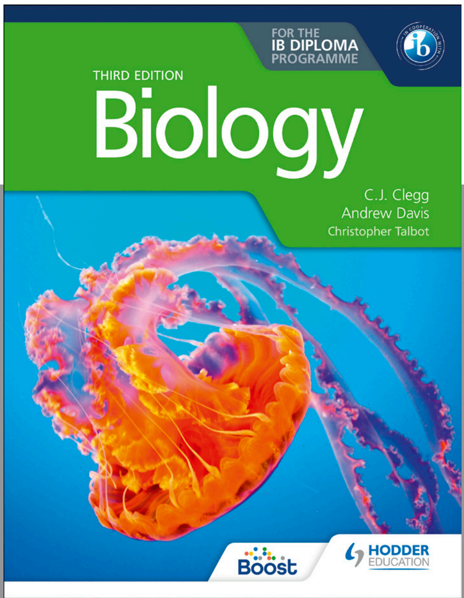

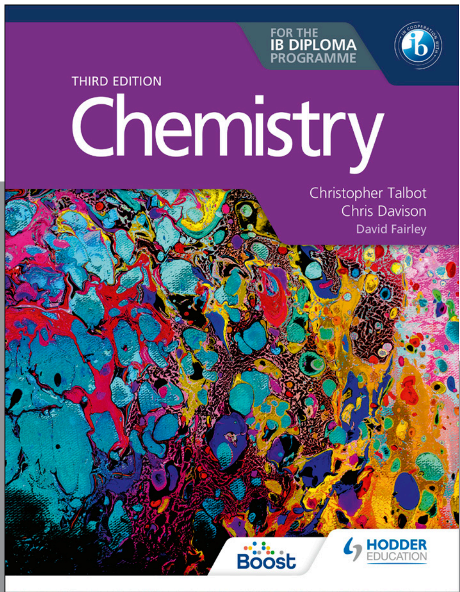

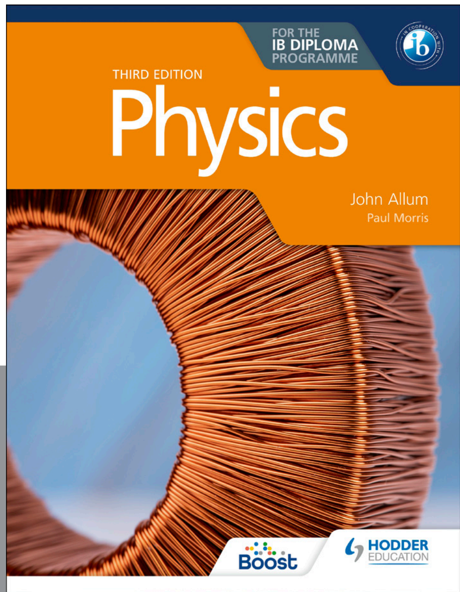

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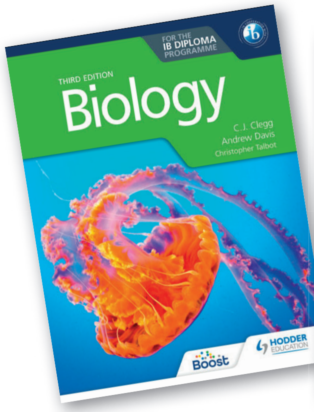

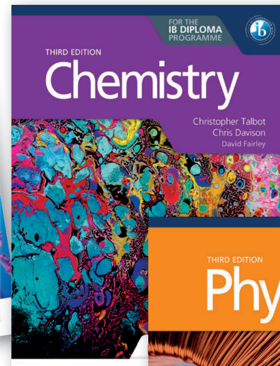

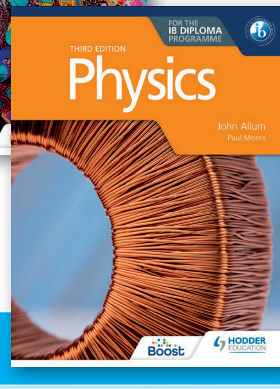

Dear IB Science educator,

We're really excited to be publishing for the new IB Sciences: Biology, Chemistry and Physics Guides for first teaching 2023, and first assessment 2025.

We are now going into third editions of our bestselling and much-loved Science books! Let our trusted, experienced, and expert authors help you navigate the new syllabuses confidently with Hodder Education's co-published coursebooks, endorsed by the IB.

We asked our authors what they like about the new Guides:

Andrew Davis has taught biology for over 20 years. He is the author of several IB textbooks and digital teaching and learning resources for Diploma and MYP, including *Biology for the MYP 4&5: By Concept.*

"This new IB Biology syllabus has many exciting changes, with greater integration of concepts, content, and skills. The reorganization of content into Themes, each based around two linked concepts, enables students to gain a greater appreciation of interconnections within the subject.

The new syllabus offers greater flexibility for how the course is delivered. Each Theme follows the same path through four levels of organization: molecules, cells, organisms and ecosystems, giving the course a logical structure, which enables students to scaffold their understanding. The course can be taught by Theme, or by level of organization, or a combination of both."

Chris Talbot has taught chemistry, biology and TOK at schools in Singapore for over 20 years. He is the author of numerous science textbooks, including *Chemistry for the MYP 4&5: By Concept.*

"I like the division into Structure and Reactivity, especially in the context of Organic chemistry.

I particularly like the emphasis on fundamental chemical concepts, principles and facts and their integration and linking across traditional chemistry topics."

Chris Davison graduated with a PhD in Organic chemistry and taught at Oundle School before joining Wellington College where he teaches DP Chemistry and runs practical and theoretical based extension lessons.

"I like that the new Guide has been designed to show the interdependence of the different areas of chemistry, inorganic, organic and physical. The topics fit under two broad titles, Structure, and Reactivity, and new linking questions highlight where subject matter both builds on and leads to other areas of the Guide.

The new Guide includes fossil fuels, biofuels and fuel cells – areas which are appealing and relevant to students and which only appeared in the option module previously."

John Allum taught physics to pre-university level in international schools for more than thirty years (as a head of department). He has now retired from teaching, but lives a busy life in a mountainside village in South East Asia. He has also been an IB examiner for many years.

"It is much more diverse than previously, providing students and teachers with many opportunities for variety, expanding beyond the limitations of just pure physics.

The removal of the Options and some of the more difficult content makes the course more manageable."

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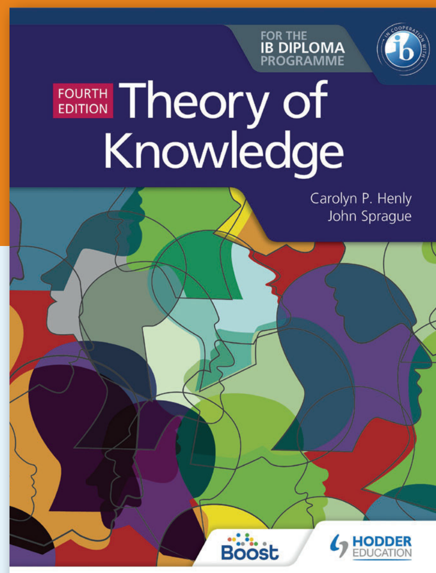
Our new co-published coursebooks support the new Guides by:

- Providing **guiding questions** at the start of each chapter along with a list of learning outcomes, each of which is mapped to the relevant assessment objective.
- Integrating **conceptual understanding** into all units, to ensure that a conceptual thread is woven throughout the course, making the subject more meaningful. This helps students develop clear evidence of synthesis and evaluation in their responses to assessment questions.
- Stimulating **creativity, curiosity, and critical thinking** with 'Inquiry', 'Tools', 'Approaches to Learning (ATL)' and 'Theory of Knowledge (TOK)' features throughout.
- Building the skills and techniques covered in the **Tools** (Experimental techniques, Technology and Mathematics). These skills are directly linked to relevant parts of the syllabus so they can be explored during delivery of the course. These skills also provide the foundation for practical work and internal assessment. They support the application and development of the inquiry process in the delivery of the new course.
- Supporting the **Inquiry** process with the new Inquiry feature, which focuses on aspects of the Inquiry cycle skills: Inquiring and designing, Collecting and processing data, Concluding and evaluating.
- Integrating **Theory of Knowledge** into your lessons and providing opportunities for cross-curriculum study with TOK links and Inquiries that provide real-world examples, case studies and questions. For Biology and Chemistry, the TOK links are written by the author of our bestselling TOK coursebook, John Sprague. For Physics the links are written by Paul Morris, our MYP by Concept series and Physics author, who has taught IB Physics for over 20 years and has also examined TOK.
- Developing **ATL** skills with a range of engaging activities with real-world applications.
- **Creating opportunities** for students to design investigations, collect data, develop manipulative skills, analyse results, collaborate with peers and evaluate and communicate their findings.
- Providing **Top tips** and **Common mistakes** to help ensure students' understanding is accurate and they are able to apply this effectively in their studies.
- **Improving performance** with short and simple knowledge-checking questions, a mixture of questions from past exam sessions and author-written exam-style questions and hints to help avoid common mistakes.
- Developing **International mindedness** by exploring how the exchange of information and ideas across national boundaries has been essential to the progress of science and illustrates the international aspects of science.
- Providing **Nature of science** boxes that encourage thinking, exploring ethical debates and learning how scientists work in the 21st century.
- Guiding students with the **IB Learner Profile** icon to help them develop as Thinkers, Risk-takers and Communicators.
- Creating opportunities for conceptual discussions and comparisons with **linking questions** at the end of each chapter.

We asked two of our expert authors what they are most proud of and what they enjoyed writing.

John Sprague

John Sprague is the author of our bestselling *Theory of Knowledge* coursebook.



"Much like how the IB Diploma is a real "programme" in the sense that all of its moving parts mesh together, Hodder Education is working to incorporate a genuine collaborative and unified vision among its author team. We've brought together writers from the science specialists and DP Core to provide opportunities for students to experience the integrative approach to knowledge that the IBDP captures. We believe that every new publication provides us an opportunity to show our readers how the construction and transfer of knowledge is a collaborative adventure."

Chris Clegg is an experienced teacher and examiner of Biology and has written many internationally-respected textbooks for pre-university courses. He was encouraged to write by his colleague and mentor at his school, textbook writer and teacher D.G. Mackean in the 1970s, and became his co-author on numerous books. He eventually took over the biology coursebook mantle from Don in the 1980s.

C. J. Clegg

"I'm proudest of the figures and diagrams which I conceived to help students to better understand complex ideas. As a reader said after the first edition of Biology for the IB Diploma, "what rockets this book above others are the brilliant illustrations in the text. They are detailed, well-annotated and ultimately support independent learning."

I gave careful thought to my choice of language and phrasing so as to be clear and precise as a means of helping students in their understanding of the subject."

To learn more about our IB DP Science series visit **hoddereducation.com/ib-dp-science**

Yours Faithfully,

Hodder Education International Team

Sample pages

FOR THE
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THIRD EDITION

Physics

John Allum

Paul Morris

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Contents

E.3 Radioactive decay

Guiding questions

- Why are some isotopes more stable than others? In what ways can a nucleus undergo change?
- In what ways can a nucleus undergo change?
- How do large, unstable nuclei become more stable?
- How can the random nature of radioactive decay allow for predictions to be made?

What is radioactivity?

Isotopes

◆ **Radioactivity** Spontaneous transmutation of an unstable nucleus, accompanied by the emission of ionizing radiation in the form of alpha particles, beta particles or gamma rays.

◆ **Transmutation** When a nuclide changes to form a different element during radioactive decay.

◆ **Radioactive** Describes a substance which contains unstable nuclei which will decay and emit radiation.

◆ **Radioisotope** or **radionuclide** Isotope / nuclide with an unstable nucleus which emits radiation when it decays.

◆ **Daughter product** The resulting nuclide when a radioisotope ('parent') decays.

The nuclei of some atoms are unstable. Spontaneous changes within an unstable nucleus can result in the emission of a particle and/or a high-energy photon. This process is called **radioactivity**. When particles are emitted, the proton number of the atom will change, so that it becomes a different element. This is called **transmutation** or radioactive decay.

A material involved in the process of radioactivity is described as being **radioactive**, while an atom with an unstable nucleus may be referred to as a **radioisotope** or **radionuclide**.

The term isotope was explained in Topic E.1. As a reminder: an *isotope* is one of two or more different nuclides of the same element (which have the same proton numbers, but different nucleon numbers).

Radioactive decay should not be confused with chemical or biological decay. The decay of a radioactive material will not usually involve any obvious change in appearance.

Most of this topic is concerned with explaining radioactivity, but a straightforward example now will help you to begin to understand all these terms, which will become more familiar as your understanding develops.

Atoms of ${}^{235}_{92}U$ have unstable nuclei, so we can describe the material as being *radioactive*. The element uranium has several *isotopes* which are all unstable / radioactive. They can all be described as *radioisotopes*. In the last two sentences, we can replace 'isotope' with 'nuclide' if we wish to stress that we are discussing nuclei.

At some (uncertain) time in the future, any ${}^{235}_{92}U$ nucleus may emit an alpha particle, ${}^{4}_{2}He$, and when this happens, we say that the nucleus has *decayed* or *transmuted*. In this example ${}^{231}_{90}Th$ (the element thorium) is formed and it may be called the *decay product* or the **daughter product**.

TOK

The natural sciences

- Does the precision of the language used in the natural sciences successfully eliminate all ambiguity?

New terminology

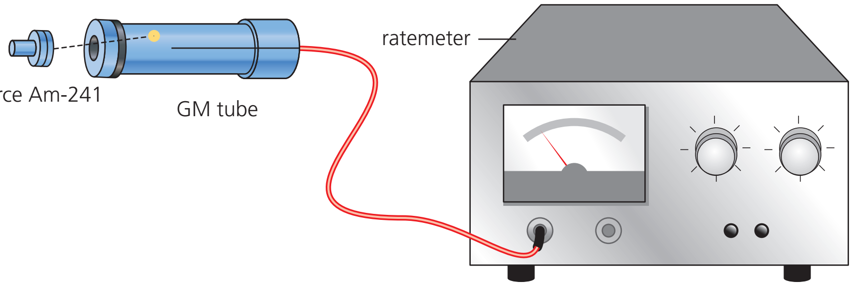
The last section illustrates a recurring theme in science education: so many new words to learn! When acquiring new scientific knowledge, is the introduction of new terms unavoidable? Does it help, or discourage, a student? Is science different from other areas of knowledge in this respect?

Radioactivity experiments

SYLLABUS CONTENT

- Effect of background radiation on count rate.

Figure E3.1 shows a typical experimental arrangement for investigating radioactivity in a school laboratory.



■ **Figure E3.1** Basic components of a radioactivity experiment

◆ **Geiger–Muller tube** Apparatus used with a counter or ratemeter to measure the radiation from a radioactive source.

◆ **Count rate (radioactivity)** The number of nuclear radiation events detected in a given time (per minute or per second) by a GM tube and a ratemeter radiation 'counter'.

◆ **Ratemeter** Meter which is connected to a Geiger–Muller tube (or similar) to measure the rate at which radiation is detected.

A tiny amount of a radioactive nuclide is contained in the 'source'. (In this example it is americium-241). When nuclear radiation emitted by the source enters the **GM (Geiger–Muller) tube** through the end 'window', it causes ionization of the gas inside and a sudden tiny burst of current. These events are 'counted' by an electronic 'counter', or **ratemeter**, and the results are expressed as a *radioactive count,* or a count per second, or per minute. (The tube and counter together are often described as a Geiger counter.) For example, if over a period of five minutes a total count of 7200 was detected, this would probably be recorded as a **count rate** of $1440\,\text{min}^{-1}$ or $24\,\text{s}^{-1}$. Many radiation detectors display a count rate directly, as seen in Figure E3.1.

Top tip!

If a radioactive count is repeated, it will probably *not* give the same result. This is because of the random nature of radioactive decays and not because of uncertainty in the measurement. For example, if a repeated count had an average of 9, it probably varied between 6 and 12, which means that a single measurement could have been unreliable. Larger counts are better. For example, if a repeated count had an average of 900, it probably varied between 870 and 930.

Tool 1: Experimental techniques

Recognize and address safety, ethical or environmental issues in an investigation

Nuclear radiation can be hazardous to humans and animals. Any experiment with radioactive materials must follow safety precautions, which include the following

- The radioactive sources must be well marked and stored securely in lead-lined boxes. They should be used for as short a time as possible.
- All experiments should be done by, or supervised by, a teacher experienced with the appropriate procedures.
- Sources should be handled with tongs and never pointed directed towards anybody.
- Students watching a demonstration should be a safe distance away. (Nuclear radiation from a point source will be absorbed to some extent in air (depending on the type of radiation) and it will also spread out.)

However, radiation sources used in schools emit very low levels of radiation.

■ **Figure E3.2** Radiation hazard sign

There are a number of things that could be investigated with the apparatus seen in Figure E3.1, including:

- How does the count rate vary when the distance between the GM tube and the source is changed?
- How is the count rate affected by placing various materials between the source and the GM tube?
- Does the count rate change with time?
- Is any count detected if the source is removed?
- Are the radiations affected by passing through electric or magnetic fields?
- How much radiation is emitted by the source every second?

◆ **Background radiation** Radiation from radioactive materials in rocks, soil and building materials, as well as cosmic radiation from space and any radiation escaping from artificial sources.

◆ **Background count** Measure of nuclear radiation from the surroundings received by a detector.

It is important to understand that there are tiny amounts of radioactive materials in almost everything around us. These materials emit very low amounts of nuclear radiation which we are all *unavoidably* exposed to everyday. Under most circumstances, this **background radiation** is low enough to be considered completely harmless.

Because of background radiation, a GM tube and ratemeter, such as seen in Figure E3.1 will record a **background count**, even when there is no obvious source of radiation present. A typical count might be 0.25 to $0.5\,s^{-1}$. If an experiment is measuring low counts, the effect of this background count is significant and it should be deducted from all readings before they are processed.

WORKED EXAMPLE E3.1

In a radioactivity experiment, a count of 42 was recorded from a source in one minute. If the background count rate in that location was $0.44\,s^{-1}$, what was the value of the count from the source after it had been adjusted for background radiation?

Answer

$42 - (0.44 \times 60) = 16\,\text{min}^{-1}$

1 Give **two** reasons why it is better to use larger count rates in radioactivity experiments.

2 a A ratemeter recorded an average 400 counts per minute from repeated measurements. Use information from the previous ‘Top tip’ box to predict the range of the count rates detected.

b Discuss which is better:
- determine a count rate over ten minutes, or
- calculate an average of ten one-minute measurements.

3 Research on the internet to find possible sources of background radiation.

4 In 15 minutes, a count of 5486 was measured when the GM tube was directed towards a radioactive source. It was known that the background count at that location was 18 per minute. Calculate the count rate, per second, due to nuclear radiation coming directly from the source.

5 At a location where the background count was $22\,\text{min}^{-1}$, in separate experiments, count rates of $50\,\text{min}^{-1}$ and $5000\,\text{min}^{-1}$ were measured.
Compare the significance of the background counts in these experiments.

Alpha particles, beta particles and gamma rays

SYLLABUS CONTENT

- The penetration and ionizing ability of alpha particles, beta particles and gamma rays.
- The changes in the state of the nucleus following alpha, beta and gamma radioactive decay.
- The radioactive decay equations involving α, β^-, β^+, γ.
- The existence of neutrinos v and antineutrinos $\overline{v}$.

◆ **Beta particle** A high-speed electron that is released from a nucleus during beta negative decay, or a high-speed positron released during beta positive decay.

◆ **Radioactive decay equation** Balanced equation which shows a radionuclide and its decay products.

In a school laboratory we can detect three different kinds of radiation emitted from radionuclides.

- alpha particles
- **beta particles**
- gamma rays (usually associated with alpha or beta emission).

Atoms of the same radionuclide always emit the same kinds of radiation

ATL E3A: Communication skills

Using terminology, symbols and communication conventions consistently and correctly

Nuclear equations

The particle(s) before the reaction are shown on the left and the products shown on the right.

Nuclear equations must balance: the sum of the nucleon numbers and proton numbers must be equal on both sides of the equation.

Alpha particles

The composition of an alpha particle is the same as a helium-4 nucleus: the combination of two protons and two neutrons, which is very stable. It has a nucleon number of 4 and a proton number of +2. Alpha particles can be represented by the symbols ${}^{4}_{2}\alpha$ or ${}^{4}_{2}\mathrm{He}$.

Clearly the emission of an alpha particle results in the loss of two protons and two neutrons from a nucleus, so that the generalized proton number of the nuclide decreases by two and a new element is formed (transmutation). This is represented in a **radioactive decay equation** as follows:

$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\alpha$$

parent nucleus → daughter nucleus + alpha particle

◆ **Nuclear equation** An equation representing a nuclear reaction. The sum of nucleon numbers (A) on the left-hand side of the nuclear equation must equal the sum of the nucleon numbers on the right-hand side of the equation. Similarly with proton numbers (Z).

The decay of radium-226 results in the emission of an alpha particle:

$${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha$$

The change to a more stable nucleus is equivalent to a decrease in nuclear potential energy. This energy is transferred to the kinetic energy of the alpha particle (and a lesser amount to the daughter nucleus).

All alpha particles from the decay of radium-226 have exactly the same (kinetic) energy: 4.7 MeV, or 7.5×10^{-13} J. (Some radionuclides emit alpha particles with different, but discrete, energies. This is explained later in this topic for HL students.)

Assuming that there are only two particles after the decay, they must move (recoil) in exactly opposite directions. This is because of the law of conservation of momentum, which also predicts that the alpha particle will have more kinetic energy and a much faster speed, because it is the less massive particle.

One mole of radium (226 g) would release a total energy of: $6.02 \times 10^{23} \times 4.71 = 2.83 \times 10^{24}$ MeV. This is a lot of energy (4.53×10^{11} J) from a relatively small mass, but the energy will be released over a very long time (because the half-life of radium-226 is about 1600 years – the concept of half-life is explained later).

Radionuclides are not generally used to transfer large amounts of energy because they are both low power and expensive, but they can provide energy for a long period of time. Alpha sources can be used to generate small amounts of electrical energy, or in places that are difficult to

Because gamma rays have no mass or charge, the composition of the emitting nucleus does not change. There is no transmutation.

Penetrating power and ionizing ability

Gamma rays cause less ionization, so that they have much greater penetrating power than alpha particles or beta particles.

We usually assume that gamma rays are not significantly absorbed in air, but if a beam is spreading out, its intensity falls with distance, following an inverse square law (assuming that they come from a point source). At least a two centimetres thickness of solid lead is needed to absorb most gamma rays. Because they are so penetrating, gamma rays are less easy to detect than alpha particles and beta particles rays.

However, because all of their energy can be transferred in one interaction, gamma rays can cause significant chemical and biological changes when absorbed in the human body. Because they are so penetrating, sources outside the body can be as dangerous as sources inside the body.

LINKING QUESTION

- Are there differences between the photons emitted as a result of atomic versus nuclear transitions?

Summary of the properties of alpha, beta and gamma nuclear radiations

Table E3.1 Summary of properties of alpha, beta and gamma radiations

Property	Alpha (α)	Beta negative (β^-)	Beta positive (β^+)	Gamma (γ)
relative charge	+2	−1	+1	0
relative mass	4	1/1840	1/1840	0
typical range in air	5 cm	30 cm	very quickly annihilates	very little absorption in air
composition	helium nucleus	electron	positron	electromagnetic wave / photon
typical speed	$\approx 10^7\,\text{m s}^{-1} = 0.1c$	$\approx 2.5 \times 10^8\,\text{m s}^{-1} \approx 0.9c$	$\approx 2.5 \times 10^8\,\text{m s}^{-1} \approx 0.9c$	$3.00 \times 10^8\,\text{m s}^{-1} = c$
notation	${}^4_2\text{He}$ or ${}^4_2\alpha$	${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta^-$	${}^{0}_{+1}e$ or ${}^{0}_{+1}\beta^+$	γ or ${}^0_0\gamma$
ionizing ability	very high	light	very quickly annihilates	very low
absorbed by	piece of paper	3 mm aluminium	very quickly annihilates	intensity halved by 2 cm lead

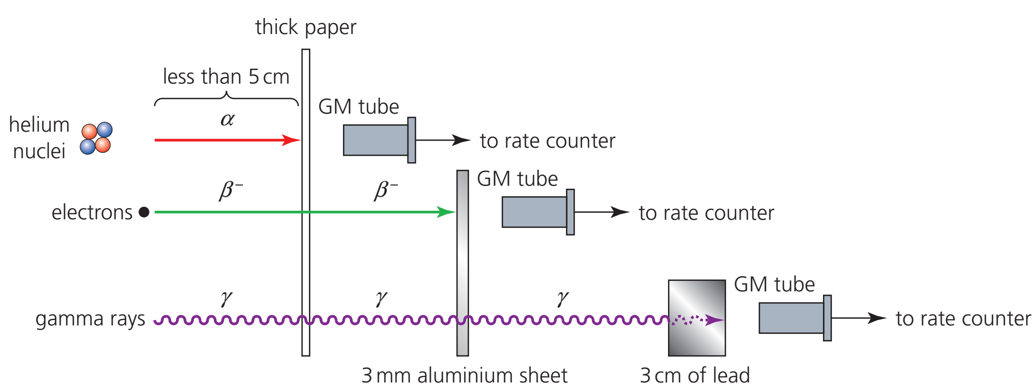


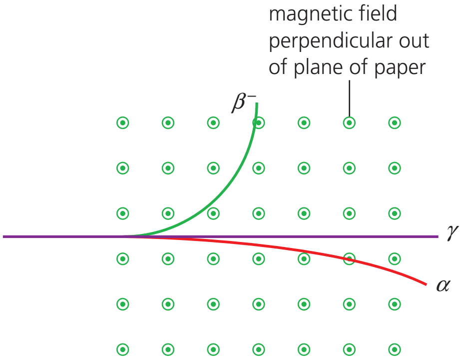
Figure E3.4 Absorption of ionizing radiations

Deflection of nuclear radiations in electric and magnetic fields

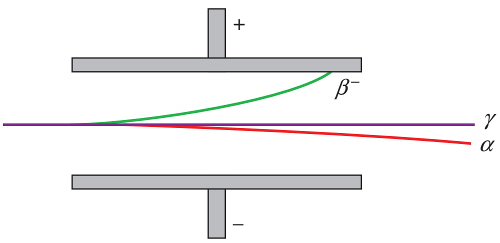
Alpha and beta radiation will be emitted in random directions from their sources, but they can be formed into narrow beams (collimated) by passing the radiation through slits.

Because a beam of alpha particles, or beta particles, is a flow of charge they will be deflected if they pass across a magnetic field (as discussed in Topic D.3).

Gamma radiation is uncharged, so it cannot be deflected in this way.



■ **Figure E3.5** Behaviour of ionizing radiations in a magnetic field



■ **Figure E3.6** Behaviour of ionizing radiations in an electric field

Figure E3.5 shows the passage of the three types of ionizing radiation perpendicularly across a strong magnetic field. Fleming's left-hand rule can be applied to confirm the deflection of the alpha and beta particles into circular paths, the magnetic force providing the centripetal force. The radius of the path of a charged particle moving perpendicularly across a magnetic field can be calculated from:

$$r = \frac{mv}{qB} \text{ (Topic D.3).}$$

An alpha particle has twice the magnitude of charge and about 8000 times the mass of a beta particle, although a typical beta particle may be moving ten times faster. Taking all three factors into consideration, we can predict that the radius of an alpha particle's path may be about 400 times the radius of a beta particle in the same magnetic field: it is deflected much less. (Note that observation of the deflection of alpha particles will require a vacuum.)

Alpha and beta radiation can also be deflected by electric fields, as shown in Figure E3.6. Alpha particles are attracted to the negative plate; beta particles are attracted to the positive plate. The combination of constant speed in one direction, with a constant perpendicular force and acceleration, produces a parabolic trajectory. This is similar to the projectile movement discussed in Topic A.1. The deflection of the alpha particles is small in comparison to beta particles, due to the same factors as discussed for magnetic deflection.

6 **a** Assuming they both have energies of 1.0 MeV, calculate the speeds of:
- **i** alpha particles,
- **ii** beta particles.

b What potential difference would be needed to accelerate electrons to the same energy?

7 Explain why the distance before the thick paper in Figure E3.4 is labelled as 'less than 5 cm'.

8 Alpha particles usually carry more energy than beta particles, or gamma rays but, paradoxically, they are less penetrating. Explain why.

9 Explain why a source of alpha radiation outside the human body may be considered to be very low risk (for example, they are used in smoke detectors), but a source inside the body is considered dangerous.

10 Explain how a beam of beta particles can be distinguished experimentally from alpha particles and gamma rays.

11 Explain why gamma rays are considered to be particularly dangerous.

12 Calculate the amount of energy carried by a gamma ray photon of wavelength 2.6×10^{-12} m?

13 An adjusted count rate of 45 min^{-1} was detected from a gamma ray source when the GM tube was 20 cm from the source.
Predict what count rate would be detected at a distance of:
a 40 cm **b** 100 cm **c** 10 m.

14 Alpha particles lose about 5×10^{-18} J of kinetic energy in each collision with an atom or molecule in the air. An alpha particle travelling through air makes 10^5 ionizing collisions with molecules or atoms in the air for each centimetre of travel.
Calculate the approximate range of an alpha particle if the particle begins with an energy of 7.0×10^{-13} J.

15 Represent in a drawing a magnetic field acting perpendicularly into the paper.
Then draw a straight line down the page to represent the original direction of a beam containing alpha particles, beta particles and gamma rays passing through the field.
Finally, show in your drawing, what happens to the three different types of radiation as they pass through the magnetic field.

Patterns of radioactive decay

SYLLABUS CONTENT

- Random and spontaneous nature of radioactive decay.
- Activity, count-rate and half-life in radioactive decay.
- Changes in activity and count rate during radioactive decay using integral values of half-life.

Radioactivity comes from unstable nuclei, but when any particular nucleus will decay and emit a particle or radiation, is completely unpredictable and uncontrollable. At some point in time an unstable nucleus will decay, but there is no way that the process can be controlled by scientists. Temperature, for example, cannot be used to control nuclear reactions (unlike chemical reactions).

Imagine that we could observe the decay of a number of unstable nuclei (another 'thought experiment'):

◆ **Random** Without pattern or predictability.

◆ **Spontaneous (decay, for example)** Without any cause, cannot be controlled.

Individual nuclei do not decay in any pattern (the decays are **random**) and each decay occurs without any obvious cause, (the decays are **spontaneous**).

Paradoxically, such randomness and unpredictability on the scale of individual nuclei, results in predictability when we consider very large numbers of nuclei.

Nature of science: Patterns and trends

Randomness

This is not the first time that the random behaviour of particles has been discussed in this course. Our understanding of the physical properties of gases developed from an appreciation of the random motions of gas molecules. Although the individual motions of gas particles are random and unpredictable, over large numbers of particles (in bulk) we can observe patterns and trends in the properties of the gas.

In everyday life, the toss of a single coin or the throw of a single dice (die) are used to make an event random and unpredictable. However, if we toss a coin enough times, we can be sure that, to a close approximation, 50% will be 'heads' and 50% will be 'tails'. Similarly, if a six-sided dice is thrown, for example 100 times, then any particular number can be expected to occur about once in every six throws (about 17 times in 100 throws). The greater the number of events, the more precisely the outcome can be predicted.

The same principle can be applied to random nuclear decays: we might say, for example, that 50% of the nuclei of a particular nuclide in a source will decay during the next year.

Activity of a radioactive source

The **activity**, A, of a radioactive source is the total number of nuclei decaying every second.

Activity may also be described as the rate of decay. We usually assume that the activity of a source is equal to the number of particles emitted every second. The SI unit of (radio) activity is the **becquerel**, Bq.

1 Bq is equivalent to one decay every second and is considered to be a low activity.

The activity of a source is proportional to the number of undecayed atoms it contains.

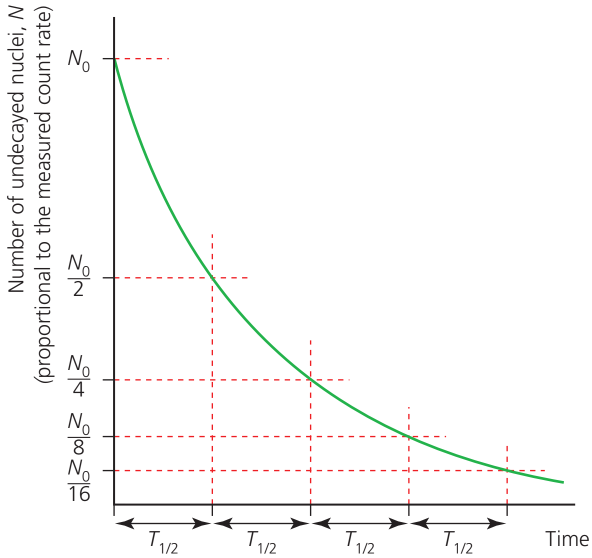


Figure E3.11 Radioactive decay curve

It should be noted that a *count rate* from a source (as being measured in Figure E3.1, for example) is *not* the same as its activity. This is because the GM tube is certainly not detecting all the radiation emitted. However, it is often assumed that a count rate is proportional to the activity.

The activity of all radioactive sources decreases with time. This is because the number of nuclei decaying every second (the activity) depends on the number of nuclei in the source which have not yet decayed. As more nuclei decay, the number remaining undecayed decreases, so the activity decreases. This reducing activity and count rate (adjusted for background count) are represented in Figure E3.11.

As explained above, half of the nuclei of any particular nuclide in a source will decay during a well-defined period of time. This is called the **half-life**, $T_{½}$, of the nuclide.

The half-life, $T_{½}$, of a radionuclide is the time it takes for half of its undecayed nuclei to decay. It is also the time taken for the activity (or count-rate) to halve.

Table E3.2 Half-life examples

Radionuclide	Half-life
uranium-238	4.5×10^9 years
radium-226	1.6×10^3 years
radon-222	3.8 days
francium-221	4.8 minutes
astatine-217	0.03 seconds

Half-lives of different radionuclides can be as short as fractions of a second, or as long as millions of years, or anything in between. See Table E3.2 for some diverse examples.

The graph seen in Figure E3.11 represents an **exponential decrease**: in equal intervals of time (shown clearly on the time axis) the count rate falls by the same fraction (one half): starting at N_0, then $N_0/2$, then $N_0/4$ and so on. In theory, for an exponential decrease, the count rate will never reduce to zero.

◆ **Activity (of a radioactive source)** The number of nuclei which decay in a given time (second).

◆ **Becquerel, Bq** The SI unit for (radio) activity. 1 Bq = one nuclear decay every second.

◆ **Half-life (radioactive)** The time taken for the activity, or count rate, from a pure source to be reduced to half. Also, equals the time taken for the number of radioactive atoms in a pure source to be reduced to half.

◆ **Exponential change** A change which occurs when the rate of change of a quantity at any time is proportional to the actual quantity at that moment. Can be an **increase** or a **decrease**.

Tool 3: Mathematics

Carry out calculations involving logarithmic and exponential functions

Any exponential decrease can be recognized by the fact that a quantity decreases to the same fraction in equal intervals of time. We usually refer to a quantity falling to *half* of its value at the end of each equal time interval, but the same behaviour also falls by *any* other chosen fraction in different time intervals.

LINKING QUESTION

- Which areas of physics involve exponential change? (NOS)

This question links to understandings in Topic C.4.

Common mistake

Many people wrongly believe that the term 'exponential' is used to describe rapid changes (increases or decreases). However, exponential changes are just as likely to be slow: consider, for example, that uranium-238 has a half-life of about 4.5 billion years.

Figure E3.12 shows a visualization that may help understanding. The same information is displayed in Table E3.3. The radionuclide americium-242 has a half-life of 16 hours.

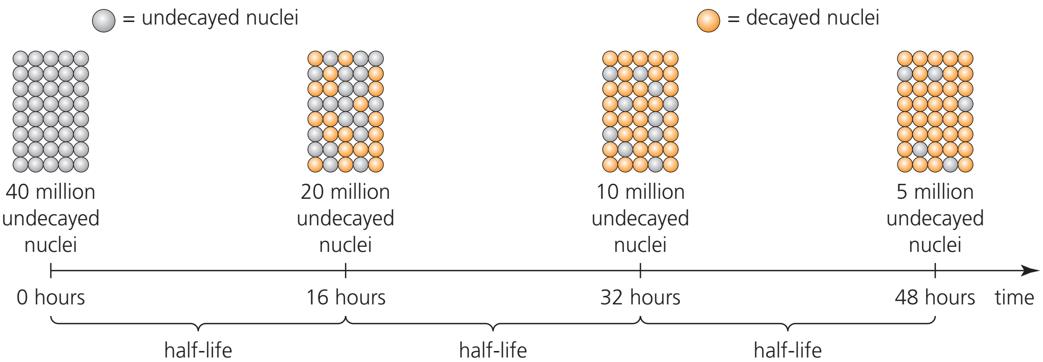


Figure E3.12 The radioactive decay of a sample of americium-242

Table E3.3

Number of undecayed nuclei	Fraction of original undecayed nuclei remaining	Number of decayed nuclei	Number of half-lives elapses	Number of hours elapsed
40×10^6	1	0	0	0
20×10^6	$\frac{1}{2}$	20×10^6	1	16
10×10^6	$\frac{1}{4}$	30×10^6	2	32
5.0×10^6	$\frac{1}{8}$	35×10^6	3	48
2.5×10^6	$\frac{1}{16}$	37.5×10^6	4	64

WORKED EXAMPLE E3.2

Radium-226 has a half-life of 1620 years. A source which has a total mass of 0.010 g contains 30% of Ra-226 and no other radionuclides.

a Calculate the mass of Ra-226 that will remain in the source after 3240 years.

b Determine how many Ra-226 nuclei will have decayed in this time.

Answer

a After two half-lives, $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ of the unstable nuclei will remain ($\frac{3}{4}$ has decayed).

Mass of Ra-226 remaining $= \frac{1}{4} \times 0.30 \times 0.010 = 7.5 \times 10^{-4}$ g

b Mass of Ra-226 decayed $= \frac{3}{4} \times 0.30 \times 0.010 = 22.5 \times 10^{-4}$ g

226 g of radium-226 contain 6.02×10^{23} atoms (Avogadro's constant)

$$\frac{22.5 \times 10^{-4}}{226} \times 6.02 \times 10^{23} = 6.0 \times 10^{18} \text{ nuclei.}$$

Experimental determination of half-life

In principle, the half-life of any radionuclide can be determined from a graph of count rate against time (as in Figure E3.11).

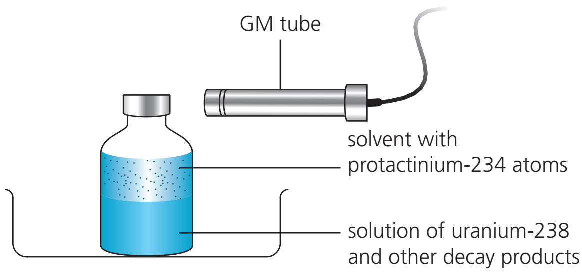


Figure E3.13 Measuring the half-life of protactinium

However, this can be difficult to obtain, for two reasons:

- Half-lives will usually be too short or too long for convenient measurement. For example, for a school experiment a half-life between a few minutes and few hours may be considered ideal, but there are not many obtainable radioisotopes that fit that description.
- When a nuclide decays it is probable that its daughter product will also be radioactive. This means that there will often be two (or more) radioisotopes with different half-lives in the same source.

The decay of protactinium-234 is widely used in schools as a demonstration of a half-life determination. (Details need not be remembered.) A compound of uranium-238 dissolved in water is contained in a very securely sealed plastic bottle. A separate layer contains a chemical which reacts with protactinium. U-238 decays to thorium-234 by emitting an alpha particle. The thorium then decays to protactinium-234 by beta-negative emission. Protactinium then decays to uranium-234 when beta-negative particles are emitted. These decays are shown below. This decay series should be understood, but not remembered.

$$^{238}_{92}\text{U} \xrightarrow{\alpha} {}^{234}_{90}\text{Th} \xrightarrow{\beta^-} {}^{234}_{91}\text{Pa} \xrightarrow{\beta^-} {}^{234}_{92}\text{Pa}$$

Of all the radionuclides present in the bottle, only Pa-234 has a suitable half-life for measurement. The protactinium compound can be separated chemically when the contents of the bottle are shaken up. The protactinium moves into the upper layer. See Figure E3.13.

Inquiry 2: Collecting and Processing data

Processing data

Table E3.4 shows the variation with time, t, of the count-rate of a sample of a radioactive nuclide X. The average background count during the experiment was 36 min^{-1}.

Table E3.4 Variation with time of the count-rate of a sample of radioactive nuclide *X*

t/hour	0	1	2	3	4	5	6	7	8	9	10
Count rate/min^{-1}	854	752	688	576	544	486	448	396	362	334	284

Plot a graph to show the variation with time of the corrected count rate and use the graph to determine the half-life of nuclide *X*.

22 One hundred dice were thrown at the same time and all the dice that showed 6 were then removed. The remaining dice were thrown again and, again, all the 6s were removed. The process was repeated another five times.

a Draw a bar chart to represent the results you would expect.

b Explain why the shape of your chart should be similar to Figure E3.11.

23 Count-rates detected every five minutes (s^{-1}) were as follows: 75, 60, 48, 38, 31, 25. Assuming that these readings were adjusted for background count, do they represent an exponential decrease? Justify your answer.

24 The initial count rate from a sample of a radioactive nuclide is 560 s^{-1} (adjusted for background count). The half-life of the nuclide is 5 minutes. Sketch a graph to show how the activity of the sample changes over a time interval of 25 minutes.

25 Explain why it would be difficult for a laboratory to provide a radioisotope with a half-life of ten minutes.

26 A radioactive isotope has a half-life of eight days and the initial count rate is 500 min^{-1}. If the average background count was 20 min^{-1}, predict the count-rate after 32 days?

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