Index

The big picture

? Guiding question(s)

- Why are some isotopes more stable than others?
- 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?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

In 2012, the Curiosity rover arrived on Mars, after a complicated landing procedure. In 2023, the rover was still active, investigating whether Mars has ever been suitable for life. It had travelled almost 30 km, climbed hundreds of metres above its starting point, analysed 36 rock samples and sent about a million images back to Earth. **Figure 1** shows the Curiosity rover on Mars.

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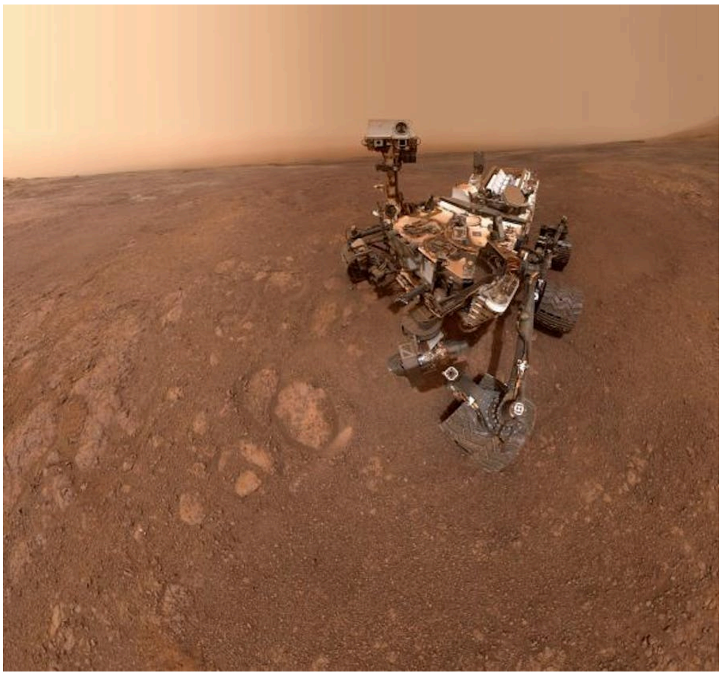
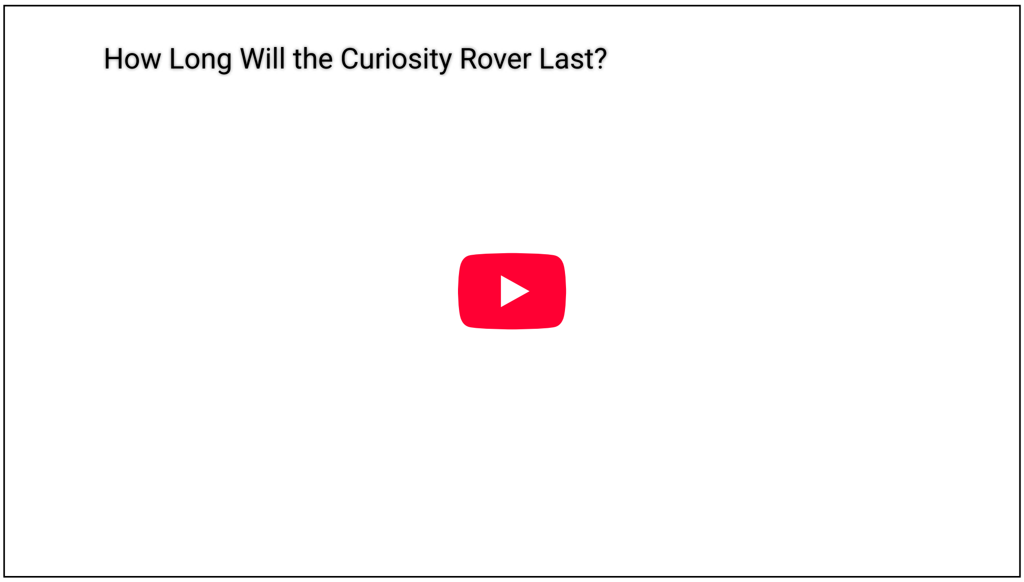


Figure 1. The Curiosity rover on Mars.

Source "Curiosity's Selfie at Rock Hall (https://photojournal.jpl.nasa.gov/catalog/PIA22960)" by NASA/JPL-Caltech/MSSS is in the public domain

How has Curiosity had enough energy for all this activity? Its energy has come from 4.8 kg of a solid material called plutonium dioxide. **Video 1** (from 2017) discusses whether Curiosity will last much longer. (It was still operating in 2023.)



Video 1. How long will Curiosity last?

How can energy be provided for so long by a lump of a single material? How did scientists work out how long Curiosity's plutonium power source would last? Could they have used another material?

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Prior learning

Before you study this subtopic make sure that you understand the following:

- The structure of an atom (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).
- Nuclear notation (for example, ${}^{12}_{6}\mathrm{C}$) (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).
- The electronvolt as a unit of energy (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).

Practical skills

Once you have completed this subtopic, you can apply your knowledge of radioactivity by going to Practical 9: Determining the half-life of random processes as a simulation of radioactive decay (/study/app/physics/sid-423-cid-762593/book/determining-the-half-life-of-random-processes-id-46753/).

E. Nuclear and quantum physics / E.3 Radioactive decay

Radioactive decay

E.3.1: Isotopes E.3.7: Alpha, beta and gamma decay E.3.8: Radioactive decay equations E.3.9: Neutrinos and antineutrinos

Learning outcomes

By the end of this section you should be able to:

- Outline what isotopes are and recognise that some isotopes are unstable.
- Describe the changes to the nucleus that occur during alpha decay, beta decay and gamma decay and use radioactive decay equations.
- Understand that neutrinos and antineutrinos exist.

In 1896, the French physicist Henri Becquerel placed a photographic plate wrapped in black paper in a drawer. On top of it, he left a sample of a chemical compound containing uranium. When he processed the photographic plate, it appeared as shown in **Figure 1.** Becquerel had placed a metal cross between the uranium compound and the wrapped plate, and its ‘shadow’ can be seen in the lower half of the image.

Student view

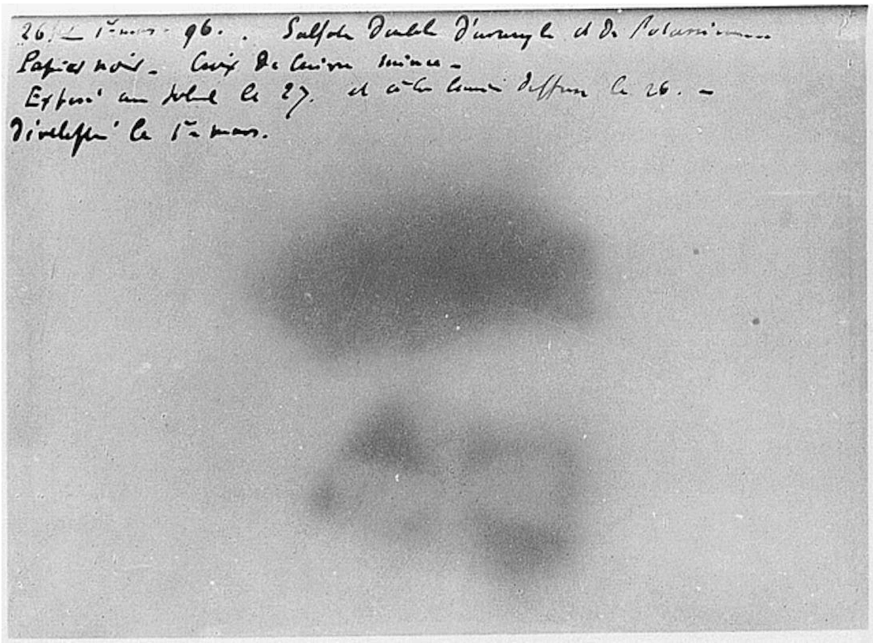

Figure 1. The photographic plate that led to the discovery of nuclear radiation.

Source: "Becquerel-plate-01 (https://en.wikipedia.org/wiki/File:Becquerel-plate-01.png)" by Henri M. Becquerel is in the public domain

More information for figure 1

The image is a photographic plate from 1896 that appears aged and faded. The top section contains handwritten text in French, likely annotations by Henri Becquerel. Below the writing, the plate exhibits a blurry, shadow-like impression of a metal cross, created by the placement of a uranium compound. This shadow is crucial, as it marks the discovery of nuclear radiation by Henri Becquerel, indicating the emission of radiation from the uranium compound affecting the plate.

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How did Becquerel's observations lead to a fundamental change in our understanding of atoms?

Isotopes

An atom of an element has a particular number of protons and electrons. However, the number of neutrons is not fixed. There can be different 'versions' of the atom, containing different numbers of neutrons. These different versions are called isotopes of the element. **Figure 2** shows three isotopes of hydrogen.

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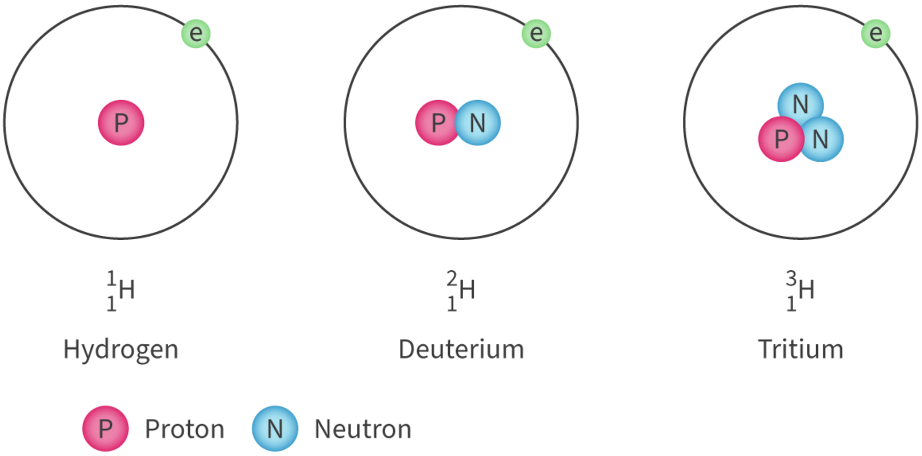

Figure 2. Three isotopes of hydrogen.

More information for figure 2

The diagram depicts three isotopes of hydrogen: Hydrogen, Deuterium, and Tritium. Each isotope is represented by an atomic model showing their subatomic particles. The first model shows Hydrogen with a single proton (P) and no neutron within the nucleus, and one electron (e) orbiting it. The second model shows Deuterium containing one proton and one neutron (N) in the nucleus, with one electron orbiting. The third model depicts Tritium with one proton and two neutrons in the nucleus, alongside one orbiting electron. Below each model, the isotopes are labeled with their respective symbols: ^{1}H for Hydrogen, ^{2}H for Deuterium, and ^{3}H for Tritium. Colors differentiate protons in pink and neutrons in blue.

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Making connections

We use nuclear notation to describe the particles in an atom (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).

What do the two numbers in ^3_1H mean?

We can also refer to the three isotopes of hydrogen as hydrogen-1, hydrogen-2 and hydrogen-3. The number refers to the number of nucleons (protons and neutrons) in the nucleus.

A nuclide is any specific type of nucleus, where the type is determined by the numbers of protons and neutrons. A particular type of nucleus can be referred to as either a nuclide or an isotope.

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Theory of Knowledge

If we did not have the word 'isotope', we would need to use a phrase such as 'atoms with the same number of protons but different numbers of neutrons'. How might that affect our ability to think and talk about isotopes?

The term 'isotope' was created in 1913 for atoms of the same element that showed differences in behaviour. The desire to explain the existence of isotopes helped to motivate the discovery of the neutron nearly 20 years later, which then led to further progress in our understanding of atoms. Does terminology help science to progress?

We do not have a simple term that means 'atoms with the same number of neutrons but different numbers of protons'. Why do you think this is? Do you think it matters?

After the discovery of the atomic nucleus in 1909, scientists realised that Becquerel radiation comes from the nuclei of atoms, and so it became known as nuclear radiation.

When a nucleus emits radiation, the nucleus is said to undergo radioactive decay. A nucleus that can do this is described as unstable, while a nucleus that will not decay is stable. An element can have stable and unstable isotopes.

Work through the activity to investigate stable and unstable isotopes.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Open the isotopes simulation.

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Interactive 1. Investigate stable and unstable isotopes.

More information for interactive 1

In this interactive simulation, users will explore the nature of isotopes by constructing atomic nuclei with varying numbers of neutrons and determining their stability. The goal is to understand the relationship between protons, neutrons, and nuclear stability, gaining insights into the behavior of different elements and their isotopes. By modifying atomic nuclei, users can investigate how changes in neutron count influence stability and lead to the emission of radiation.

Selecting the 'Isotopes' tab allows users to construct and examine isotopes by modifying neutron counts. Enable Visual Aids by clicking the green buttons next to 'Abundance in Nature' and 'Symbol' to display nuclear notations and see how common or rare certain isotopes are.

Select an element from the periodic table to begin isotope construction.
To construct an isotope, drag neutrons from the 'Neutrons' container into the selected nucleus. The simulation will indicate whether the isotope is stable or unstable based on neutron-proton ratios. Add or remove neutrons to explore different isotopes of the same element. Compare the stability of isotopes with different neutron numbers. Repeat the process with various elements, noting patterns in stability across the periodic table. Stable isotopes remain unchanged over time, while unstable isotopes undergo radioactive decay, emitting radiation and transforming into different elements.

Select one element; for example, select the Hydrogen-1 element (which has only a single proton inside the nucleus). Place a neutron from the container into the nucleus of the hydrogen atom. The resulting isotope, "Hydrogen-2," is a stable isotope of hydrogen. Again, adding one neutron results in the formation of an unstable isotope, "Hydrogen-3."

Through this process, users can visualize the principles of nuclear notation, where the atomic number (number of protons) and the nucleon number (total number of protons and neutrons) define the identity and mass of an atom. The simulation also provides insight into the distinction between nuclides and isotopes, illustrating how nuclides refer to specific atomic nuclei while isotopes represent different forms of an element with the same number of protons but varying neutron counts.

Through this simulation, users will develop an intuitive understanding of nuclear stability, radioactivity, and the natural distribution of isotopes. By manipulating atomic structures, they will gain insight into why some isotopes exist abundantly in nature while others are highly unstable and radioactive.

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You are going to build different isotopes and see whether they are stable or unstable.

1. Select the ‘Isotopes’ tab.
2. Click the green button next to ‘Abundance in Nature’ and click the green button next to ‘Symbol’ to show nuclear notations.
3. Choose an element by clicking on an element symbol below the ‘Periodic Table'.
4. Drag neutrons from the ‘Neutrons’ container into the purple circle to create an isotope. Is the isotope stable or unstable?
5. Create a different isotope with a different number of neutrons. Is the isotope stable or unstable?
6. Repeat with different elements and different isotopes. As well as adding neutrons, you can also remove neutrons by dragging them to the container. Are isotopes with equal numbers of protons and neutrons always stable? Explore the stability of isotopes with: more protons than neutrons; more neutrons than protons.

Nature of Science

Aspect: Global impact of science

It is often said that Becquerel discovered nuclear radiation. However, although Becquerel was the first to observe one of its effects, the discovery of nuclear radiation was a process that took many years and the work of many scientists.

Science usually develops through the work of different scientists, who sometimes collaborate. Progress relies on the publication of discoveries so scientists can learn from each other’s work and build on it.

Polish—French physicist Marie Skłodowska-Curie won the 1903 Nobel Prize in physics jointly with Becquerel and her husband Pierre, for the discovery of what was termed ‘spontaneous’ radioactivity. She also won the 1911 Nobel Prize in chemistry for the discovery of new elements.

Radioactive decay

Alpha decay

An alpha particle, α, is made up of two protons and two neutrons. It is identical to a nucleus of helium-4, the most common isotope of helium. The alpha particle is sometimes represented using the symbol for helium, ${}^{4}_{2}\text{He}$. The alpha particle has two protons so it has a charge of +2.

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During alpha decay, a parent nucleus emits an alpha particle and changes (decays) into a daughter nucleus with fewer protons. This means that the daughter nucleus is a different element.

The general radioactive decay equation for alpha decay is:

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

where:

$^{A}_{Z}\mathrm{X}$ is the parent nucleus, with chemical symbol X, nucleon number A and proton number Z (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).

$^{A-4}_{Z-2}\mathrm{Y}$ is the daughter nucleus, which has two fewer protons and two fewer neutrons than the parent nucleus.

$^{4}_{2}\alpha$ is the alpha particle, with four nucleons (two protons and two neutrons).

Study skills

In radioactive decay equations, the sum of the nucleon numbers is the same on both sides of the equation because the total number of nucleons is the same before and after the decay.

The sum of the proton numbers is also the same on both sides of the equation because the total charge is the same before and after the decay.

An example of alpha decay is the decay of uranium-238. A uranium-238 nucleus can decay into a thorium-234 nucleus by the following reaction:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$$

Worked example 1

Give the radioactive decay equation for the alpha decay of radium-226 ($^{226}_{88}\mathrm{Ra}$), into radon (Rn).

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

The parent nucleus is $^{226}_{88}\mathrm{Ra}$, so the nucleon and proton numbers of the daughter nucleus are 226 – 4 and 88 – 2, respectively. The daughter nucleus is $^{222}_{86}\mathrm{Rn}$.

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Aspect: Experiments

How did scientists deduce that alpha decay is the emission of a helium-4 nucleus? Various experiments provided evidence for this but there was some doubt until an experiment by Ernest Rutherford and Thomas Royds in 1909 (see subtopic E.1.1 (/study/app/physics/sid-423-cid-762593/book/atoms-and-photons-id-46593/)). They trapped alpha particles then allowed the particles to pick up electrons and become neutral. They observed the emission spectrum (see subtopic B.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43777/)) of the resulting gas and compared it with the known emission spectrum of helium gas, and found they were the same.

Beta-minus decay

Beta-minus decay involves the emission of a beta-minus particle (β^-) from the nucleus. A beta-minus particle is an electron, and the symbol can also be e^- or ${}_{-1}^{0}e$. Its nucleon number is 0 because the electron is not composed of nucleons, and it has very little mass compared with a nucleon. Its proton number is –1, which means that its charge is –1.

During beta-minus decay, a neutron in the nucleus changes into a proton and an electron. The proton remains in the nucleus and the electron is ejected.

When a nucleus undergoes beta-minus decay, its neutron number decreases by one and its proton number increases by one. The change in proton number means that the nucleus becomes a nucleus of a different element.

The general radioactive decay equation for beta-minus decay is:

$${}_{Z}^{A}\mathrm{X} \rightarrow {}_{Z+1}^{A}\mathrm{Y} + {}_{-1}^{0}\beta + \overline{v}$$

where:

- ${}_{Z}^{A}\mathrm{X}$ is the parent nucleus
- ${}_{Z+1}^{A}\mathrm{Y}$ is the daughter nucleus, which has the same number of nucleons as the parent nucleus, but one more proton
- ${}_{-1}^{0}\beta$ is the beta-minus particle
- $\overline{v}$ is a type of particle called an antineutrino

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An antineutrino can also have the symbol ${}^{0}_{0}\overline{v}$. The two zeros show that the antineutrino has very low mass and no charge.

Antineutrinos are very hard to detect, and their existence was not even suspected until over thirty years after the discovery of beta decay.

An example of a beta-minus decay is the decay of thorium-234 into protactinium-234:

$$ {}^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\beta + \overline{v} $$

Beta-plus decay

In 1934, Frédéric and Irène Joliot-Curie (daughter of Marie Skłodowska-Curie) discovered a fourth type of nuclear radiation, in which beta-plus particles (also known as positrons or antielectrons) were emitted.

A beta-plus particle, β^{+}, is a particle with the same mass as an electron and the same amount of charge, but its charge is positive instead of negative. The symbol can also be e^{+} or ${}^{0}_{1}e$.

Radioactive decay by emission of a beta-plus particle is called beta-plus decay. Beta-plus decay occurs when a proton in the nucleus changes into a neutron and a beta-plus particle. The neutron remains in the nucleus and the beta-plus particle is emitted.

When a nucleus undergoes beta-plus decay, its neutron number increases by one and its proton number decreases by one. The change in proton number means that the nucleus becomes a nucleus of a different element.

The general radioactive decay equation for beta-plus decay is:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + {}^{0}_{1}\beta + v $$

where:

- is the parent nucleus
- is the daughter nucleus, which has the same number of nucleons as the parent nucleus, but one less proton
- ${}^{0}_{1}\beta$ is the beta-plus particle
- v is a type of particle called a neutrino.

Student view

A neutrino can also have the symbol ${}^{0}_{0}v$. The two zeros show that it has very little mass compared with a nucleon, and no charge.

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An example of a beta-plus decay is the decay of phosphorus-30 into silicon-30:

$$^{30}_{15}\mathrm{P} \rightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\beta + v$$

The term beta decay is sometimes used as a collective name for beta-minus decay and beta-plus decay.

Worked example 2

$^{23}_{12}\mathrm{Mg}$ decays into $^{23}_{11}\mathrm{Na}$.

Determine the type of decay and explain your answer.

In this decay, the nucleon number stays the same and the proton number decreases by 1. This occurs in beta-plus decay, in which a proton changes into a neutron and a beta-plus particle.

Gamma decay

Gamma rays, *y*, consist of high-energy photons. The symbol can also be $^{0}_{0}\gamma$, where the two zeros indicate that the mass is zero and gamma rays have no charge (because they are a form of electromagnetic radiation).

An atom's nucleus can be excited, meaning that it has excess energy. In gamma decay, an excited nucleus loses energy by emitting a gamma ray.

The general radioactive decay equation for gamma decay is:

$$^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + \gamma$$

where:

- $^{A}_{Z}\mathrm{X}^{*}$ is the parent nucleus (the * indicates that the nucleus is in an excited state)
- $^{A}_{Z}\mathrm{X}$ is the nucleus after the decay, which is the same nucleus, but it is no longer excited
- *y* is the gamma ray

Gamma decay is the only type of radioactive decay that does not cause the nucleus to become a different element.

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Decay series

A radioactive decay does not always produce a stable daughter nuclide. If the daughter nuclide is unstable, it will also decay. In some cases, there is a series of decays, or decay series, that does not end until a stable nuclide is reached.

Figure 3 shows a decay series that begins with uranium-238 and ends with lead-206. (Gamma decay is not shown because it does not cause a change from one element into another.)

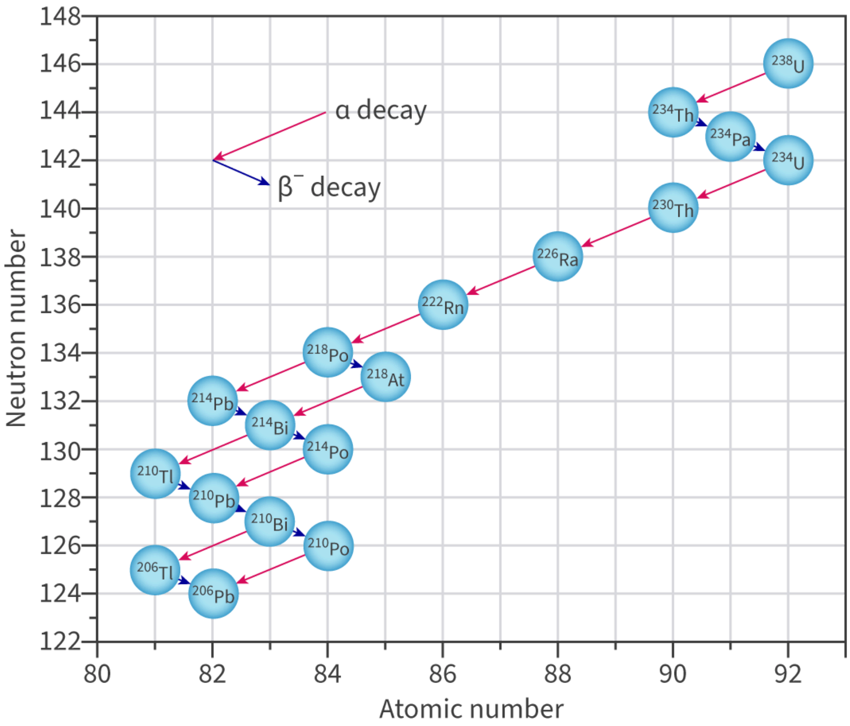

Figure 3. Radioactive decay series.

More information for figure 3

The diagram depicts a radioactive decay series starting from uranium-238 and ending with lead-206. The X-axis represents atomic numbers ranging from approximately 82 to 92, while the Y-axis denotes neutron numbers from about 122 to 148. The series starts at the top with uranium-238. The decay chain progresses with arrows indicating alpha (α) and beta (β) decays through various isotopes: thorium-234, protactinium-234, uranium-234, thorium-230, radium-226, radon-222, polonium-218, and others. The decay shown includes common isotopes like lead-214, bismuth-214, polonium-214, and thallium-210, finally ending at lead-206. Gamma decay is not charted as it doesn't alter the elemental identity. The diagram uses connecting arrows to show decay paths and isotope relationships.

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Study skills

You are not expected to know which type of decay any particular nucleus undergoes, or which isotopes are stable or unstable. You are also not expected to know the element symbol or proton number of any element. However, you should be able to use deduction to solve problems relating to radioactive decay.

Worked example 3

A nucleus of a thorium nuclide, ${}^{232}_{90}\text{Th}$, undergoes a series of alpha and beta-minus decays to become a nucleus of a radium nuclide, ${}^{224}_{88}\text{Ra}$.

Deduce the number of alpha decays and the number of beta-minus decays that take place.

The effects of alpha and beta-minus decays on a nucleus can be summarised as:

alpha decay: ${}^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y}$

beta-minus decay: ${}^{A}_{Z}\text{X} \rightarrow {}^{A}_{Z+1}\text{Y}$

${}^{224}_{88}\text{Ra}$ has eight fewer nucleons than ${}^{232}_{90}\text{Th}$. This change must be caused by alpha decays, since beta-minus decays do not change the nucleon number.

In alpha decay, the nucleus loses four nucleons, so two alpha decays must take place.

If no beta-minus decays had occurred, the resulting nucleus would be ${}^{224}_{86}\text{Rn}$ because two alpha decays would change the proton number to 90 − 4 = 86.

The proton number of ${}^{224}_{88}\text{Ra}$ is 88, not 86.

Since a beta-minus decay increases the proton number by one, there must be two beta-minus decays.

Therefore, there are two alpha decays and two beta-minus decays.

Work through the activity to check your understanding of radioactive decay.

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Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Answer the following questions on radioactive decay.

1. Is each statement true or false?

   (a) Beta decay does not cause a change in the nucleon number of a nucleus.
   (b) In beta-minus decay, the parent nucleus and daughter nucleus can be isotopes of the same element.
   (c) Two beta-plus decays change the numbers of each type of particle in a nucleus in exactly the same way as one alpha decay.

2. Write a decay equation for each of the following decays.

   (a) ${}^{3}_{1}\mathrm{H}$ decays into a helium (He) nucleus by beta-minus decay.
   (b) ${}^{238}_{94}\mathrm{Pu}$ undergoes a single decay to become an isotope of uranium (U), which has 92 protons.
   (c) An excited nucleus of barium-137, which has 81 neutrons, undergoes gamma decay.
   (d) An isotope of nitrogen (N) has 7 protons and 6 neutrons, and it becomes an isotope of oxygen (O) by emitting a beta-plus particle.
3. The changes to a nucleus through one or more decays can be represented by arrows on a graph of neutron number against proton number). One division represents a change by one in the neutron or proton number.

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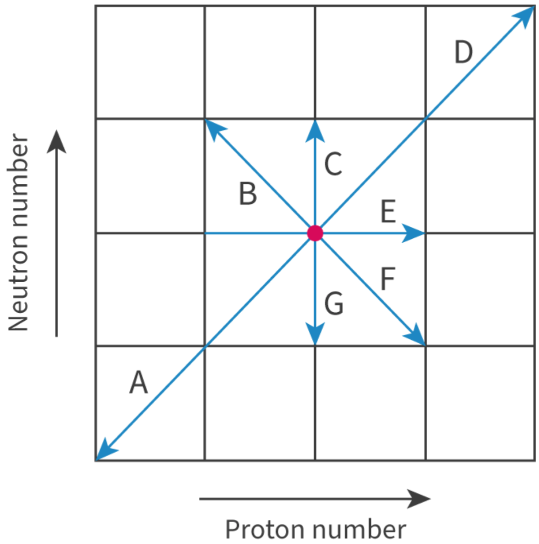

Figure 4. Graph of neutron number against proton number.

More information for figure 4

The image is a graph with 'Neutron number' on the Y-axis and 'Proton number' on the X-axis. The graph displays several arrows originating from a central point, labeled A through G. Each arrow represents changes in neutron or proton numbers due to nuclear decay processes. The X and Y axes are divided into equal intervals, with each division representing a change by one in the neutron or proton number. Arrows such as A, B, C, D, E, F, and G indicate various directions on the graph, showing possible outcomes of different types of decay, including alpha, beta-minus, and beta-plus decays. The description is necessary to explain how these decays alter the numbers of protons and neutrons.

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(a) Identify the arrow that shows the effect on the proton and neutron numbers of:
  (i) an alpha decay
  (ii) a beta-minus decay
  (iii) a beta-plus decay

(b) Explain why gamma decay cannot be represented by an arrow on this graph.

4. A polonium-220 nucleus can undergo a series of three decays (not including gamma decay) to become a polonium-216 nucleus. Explain how this series of decays can end in a nucleus of the same element as the starting nucleus. (Only consider alpha decay, beta-plus decay and beta-minus decay as possible types of decay.)

1 (a) True. In beta-minus decay and beta-plus decay, a nucleon changes into a different type of nucleon, so the total number of nucleons remains the same.

(b) False. The daughter nucleus has one more proton than the parent nucleus, so it is a different element.

(c) False. In both cases, the proton number decreases by two, but alpha decay reduces the number of nucleons by four, whereas two beta-plus decays leave the nucleon number unchanged.

2 (a) ${}^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\beta + \overline{v}$

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(b) $^{238}_{94}\mathrm{Pu} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{4}_{2}\alpha$

(c) $^{137}_{56}\mathrm{Ba}^{*} \rightarrow {}^{137}_{56}\mathrm{Ba} + \gamma$

(d) $^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{O} + {}^{0}_{1}\beta + v$

3 (a) (i) A, because the nucleus loses two protons and two neutrons.

(ii) F, because the nucleus loses a neutron but gains a proton.

(iii) B, because the nucleus loses a proton but gains a neutron.

(b) In gamma decay, the numbers of protons and neutrons do not change.

4 If the final nucleus and the initial nucleus are isotopes of the same element, they must have the same proton number. The nucleon number decreases by four, from 220 to 216, so there must be one alpha decay. This reduces the proton number by two, but it must stay the same overall. A beta-minus decay increases the proton number by one while a beta-plus decay decreases the proton number by one. So the other two decays are beta-minus decays. There is one alpha decay and two beta-minus decays.

6 section questions

Question 1

SL HL Difficulty:

1 Isotopes ✓ are atoms of the same element that have different numbers of 2 neutrons ✓ but the same number of 3 protons ✓ in the nucleus. They can be stable or unstable.

Accepted answers and explanation

#1 Isotopes

#2 neutrons

#3 protons

General explanation

Isotopes are stable or unstable atoms of the same element that have different numbers of neutrons but the same number of protons in the nucleus.

Question 2

SL HL Difficulty:

In 1 beta-minus ✓ decay, one of the emitted particles is an antineutrino.

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In 2 gamma ✓ decay, the daughter nucleus is the same as the parent nucleus.

In 3 alpha ✓ decay, the emitted particle can become a neutral atom if it gains two electrons.

Accepted answers and explanation

#1 beta-minus
beta minus

#2 gamma

#3 alpha

General explanation

In beta-minus decay, one of the emitted particles is an antineutrino.

In gamma decay, the daughter nucleus is the same as the parent nucleus.

In alpha decay, the emitted particle can become a neutral atom if it gains two electrons.

Question 3

SL HL Difficulty:

Which is the correct radioactive decay equation for the beta-plus decay of an isotope of nitrogen (N) into $^{13}_{6}\mathrm{C}$ (https://www.codecogs.com/eqnedit.php?latex=%5Cmathrm%7B%5E%7B13%7D_%7B6%7DC%7D#0)?

1 $^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\mathrm{e} + v$ ✓

2 $^{13}_{6}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\mathrm{e} + v$

3 $^{13}_{5}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\mathrm{e} + \overline{v}$

4 $^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{1}\mathrm{e} + \overline{v}$

Explanation

In beta-plus decay, a beta-plus particle and a neutrino (v (https://www.codecogs.com/eqnedit.php?latex=%5Cmathrm%7B%5Cnu%7D#0)) are emitted by a nucleus. A proton changes into a neutron, so the proton number decreases by one, while the number of nucleons does not change. The parent nucleus has one more proton than the daughter nucleus, and so it is $^{13}_{7}\mathrm{N}$ and not $^{13}_{5}\mathrm{N}$.

Question 4

SL HL Difficulty:

Student view

A nucleus has nucleon number *A* and proton number *Z*.

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The nucleus undergoes a series of decays: three alpha decays, four beta-minus decays and seven gamma decays.

Which row of the table, A, B, C or D, shows the nucleon number and proton number of the nucleus after these decays?

	Nucleon number	Proton number
A	$A - 6$	$z - 12$
B	$A - 6$	$Z + 4$
C	$A - 12$	$Z - 2$
D	$A - 12$	$Z + 10$

1 C ✓

2 A

3 B

4 D

Explanation

Gamma decay does not change the nucleon number or proton number of a nucleus and so has no bearing on the answer here.

In each alpha decay, the nucleus loses four nucleons, two of which are protons. So three alpha decays would change the numbers to $A - 12$ and $Z - 6$.

In each beta-minus decay, a neutron becomes a proton and a beta-minus particle (electron). This does not change A but it increases Z by one. So the four beta-minus decays change the proton number to $Z - 6 + 4 = Z - 2$, while the final nucleon number is $A - 12$.

Question 5 SL HL Difficulty:

A radium nucleus (atomic number 88) emits an alpha particle and changes into a radon-222 nucleus.

Before undergoing alpha decay, the radium nucleus had 1 138 ✓ neutrons.

Student
view

Accepted answers and explanation

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#1 138

General explanation

After an alpha particle is emitted, the nucleus has two fewer protons and two fewer neutrons.

If the radium nucleus has 88 protons, the radon nucleus must have 86 protons:

222 − 86 = 136 neutrons

The radium nucleus had:

136 + 2 = 138 neutrons

Question 6

SL HL Difficulty:

A nucleus of $^{A}_{Z}\mathrm{X}$ undergoes a series of decays to become a nucleus of $^{A-8}_{Z-1}\mathrm{Q}$.

All of the decays are alpha decay, beta-minus decay or gamma decay.

Determine the number of beta-minus decays that occur.

1 3 ✓

2 1

3 7

4 2

Explanation

Gamma decay does not change the nucleon or proton numbers, so it is not possible, or necessary, to know how many gamma decays occur.

Beta-minus decay does not change the nucleon number, but alpha decay reduces it by four. The nucleon number changes from A to $A-8$, so there must be two alpha decays.

Each alpha decay reduces the proton number by two, so if there were no beta-minus decays, the final nucleus would be $^{A-8}_{Z-4}\mathrm{Q}$. However, the final nucleus is , which has three protons more.

Beta-minus decay increases the proton number by 1, so there must have been three beta-minus decays.

E. Nuclear and quantum physics / E.3 Radioactive decay

Student view

Nuclear radiation

Learning outcomes

By the end of this section you should be able to:

- Outline how background radiation affects the count rate of a source of nuclear radiation.
- Describe the penetrating and ionising abilities of alpha particles, beta particles and gamma rays.

Your body is partly composed of electrons, around 10^{28} of them, but electrons from beta-minus decay can harm you. How is this possible?

Background radiation

A Geiger-Müller tube is used to detect nuclear radiation (**Figure 1**). It can detect beta particles and gamma rays, and some models can also detect alpha particles.

The tube is connected to a counter that displays a count rate, which is the number of emissions of nuclear radiation detected per unit time interval. Count rate is often measured in counts per minute or counts per second. An average rate is usually taken over a number of time intervals because count rates display random fluctuations (see section E.3.3a (/study/app/physics/sid-423-cid-762593/book/half-life-id-46544/)).

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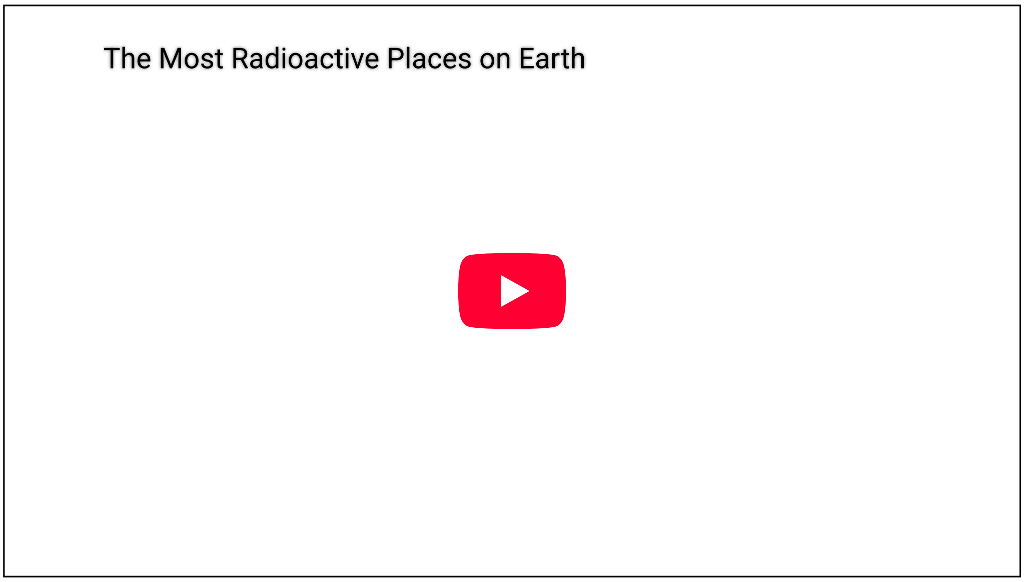
Figure 1. A Geiger-Müller tube attached to a counter.

A Geiger counter typically shows an average count rate greater than zero even when no radioactive source has been placed nearby. This is because of background radiation.

The emission of nuclear radiation (alpha particles, beta particles and gamma rays) occurs naturally in our environment. There are various causes, including emission by radioisotopes (radioactive isotopes) within rocks, emission by radon gas released by rocks, cosmic rays from the Sun, and naturally-occurring radiation from food and drink.

International Mindedness

Our exposure to background radiation is affected by where in the world we live. The radioactivity of rocks varies with location, and our exposure to cosmic rays increases with altitude. **Video 1** shows some of the most radioactive places on Earth. The most extreme cases are a result of human activity.



Video 1. The most radioactive places on Earth.

Parts of Ramsar, a city in northern Iran, have the highest known levels of natural background radiation in the world. This is because of relatively large concentrations of radium in the rocks, soil and water. Exposures as high as over 200 millisieverts per year have been measured in inhabited areas. Despite this, no obvious negative effect on residents' health has been found.

Student view

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Figure 2 shows a pie chart of contributions to background radiation (not including contributions due to occupation or lifestyle factors such as frequent air travel or tobacco smoking). These are typical values – actual values vary depending on location and lifestyle factors.

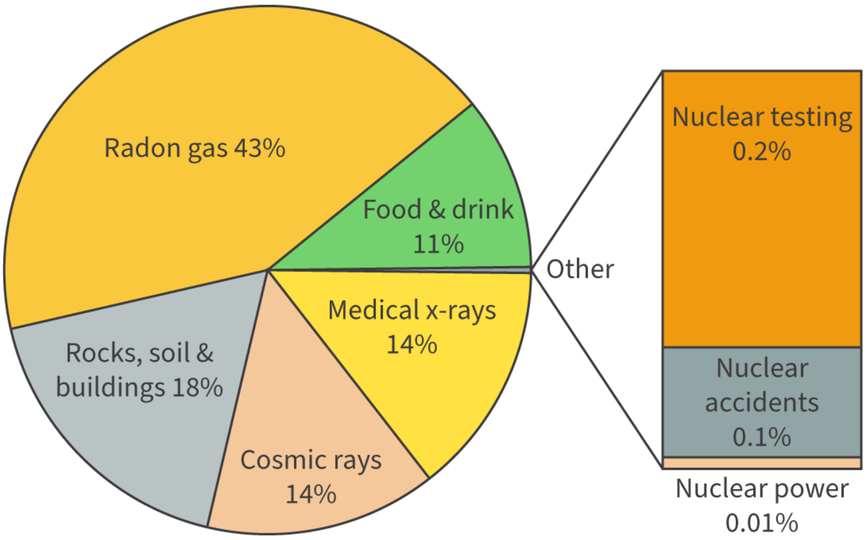

Figure 2. Percentage contributions to a person's typical background radiation exposure.

More information for figure 2

The image displays a pie chart illustrating the percentage contributions to a person's typical background radiation exposure. The largest contribution comes from Radon gas, accounting for 43% of exposure. Following that, rocks, soil, and buildings contribute 18%. Medical x-rays and cosmic rays each contribute 14% to background radiation. Food and drink add 11% to the exposure. An 'Other' category is also shown, which comprises a small segment of the pie chart. This segment is further broken down in a separated rectangular chart showing that Nuclear testing accounts for 0.2%, Nuclear accidents 0.1%, and Nuclear power 0.01% of the exposure.

[Generated by AI]

When a Geiger counter is used to measure the count rate due to a radioactive source, background radiation also contributes to the measurement.

A background count correction can be made. The average count rate in the absence of the source is measured, and this is subtracted from the measured count rate to give a corrected count rate.

Penetration ability of nuclear radiation

One of the ways in which scientists deduced that there were three types of nuclear radiation (before beta-plus decay was discovered) was by measuring how easily nuclear radiation could penetrate different materials.

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Open this Geiger-Müller tube simulation (http://www.gigaphysics.com/gmtube_lab.html). Select ‘Alpha’ from the ‘Radiation source’ drop-down menu, then select a ‘Type of barrier’. Select ‘Start Count’. Select a different type of barrier and see what happens to the count.

Repeat with the ‘Beta’ and ‘Gamma’ sources. What do you notice?

Figure 3 shows how alpha particles, beta particles and gamma rays can be reduced or stopped by different materials.

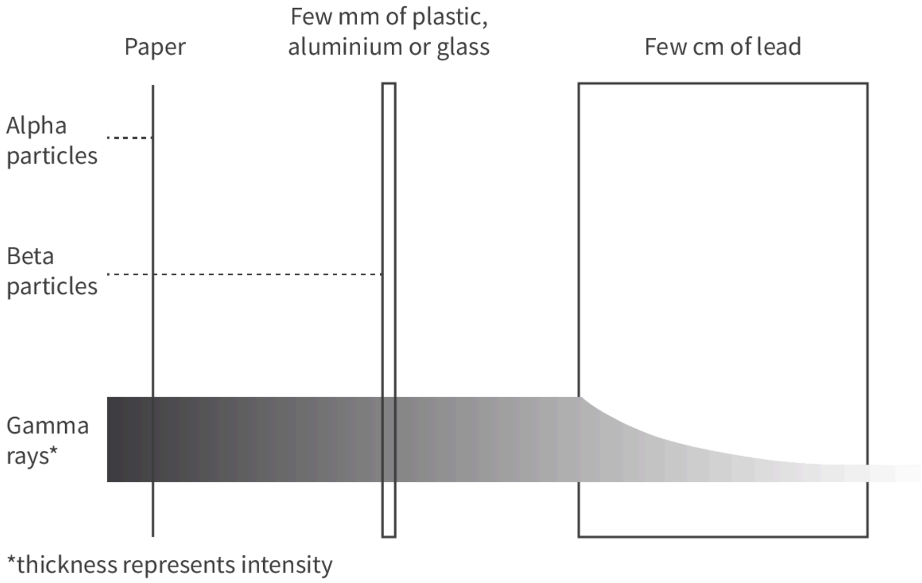

Figure 3. Penetration of materials by alpha particles, beta particles and gamma rays.

More information for figure 3

The image is a diagram illustrating the penetration abilities of alpha particles, beta particles, and gamma rays through different materials. On the left, a thin layer of paper stops alpha particles. In the center, a few millimeters of plastic, aluminum, or glass stops beta particles. On the right, a few centimeters of lead significantly reduces the intensity of gamma rays, shown by a gradient that becomes lighter as it passes through the lead. Text on the diagram indicates thickness represents intensity for gamma rays.

[Generated by AI]

Table 1 shows the penetrating abilities of alpha particles, beta particles and gamma rays and their typical range in air.

Table 1. Penetrating abilities of alpha particles, beta particles and gamma rays.

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Radiation	Typical range in air	Usually stopped by
alpha particle	3—5 (a few) centimetres	sheet of paper outermost (dead) layer of human skin
beta particle	25—100 cm	5 mm of aluminium, plastic or glass 1 cm of body tissue
gamma ray	not stopped by air but reduced in intensity; a significant percentage may travel a kilometre or more	nothing, but significantly reduced by a few centimetres of lead or several metres of concrete

Making connections

Alpha particles, beta-minus particles (electrons) and gamma rays behave differently in electric and magnetic fields Alpha particles have a relative charge of +2 and beta-minus particles have a relative charge of —1. The motion of charged particles in electric and magnetic fields is covered in subtopic D.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-45416/).

Figure 4a shows that alpha particles and beta-minus particles are deflected in opposite directions in an electric field, while gamma rays are not deflected because they have no charge. Why do you think beta-minus particles are deflected more strongly than alpha particles?

Figure 4b shows alpha particles and beta-minus particles being deflected in a magnetic field. Explain the directions of deflection using your knowledge of forces on charged particles moving in magnetic fields.

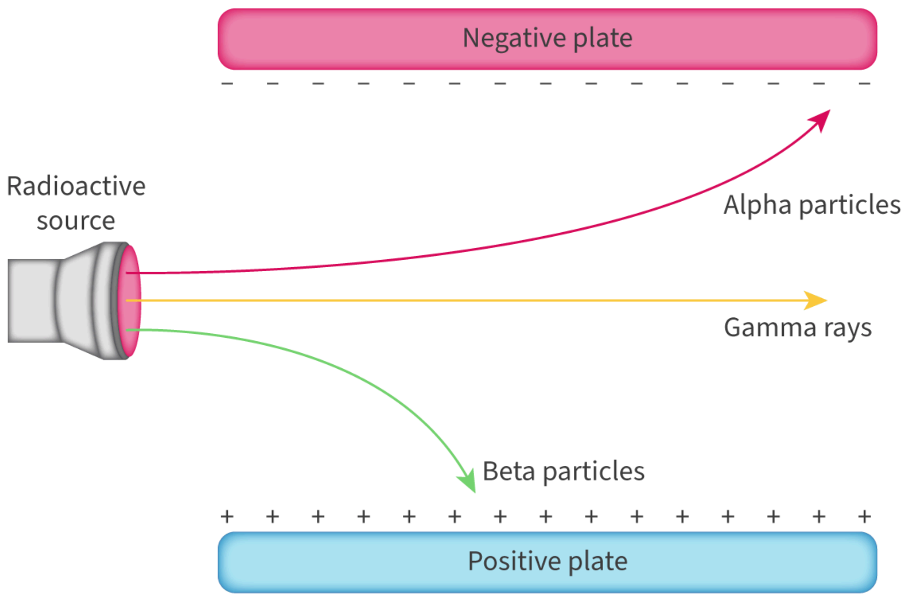

Figure 4a. The paths of alpha particles, beta-minus particles in a uniform electric field.

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More information for figure 4

The diagram illustrates the deflection of alpha, beta, and gamma rays from a radioactive source in a uniform electric field. It shows three colored vectors originating from the radiation source:

1. **Alpha particles** (pink vector): These are deflected upward towards a labeled "Negative plate." This indicates that alpha particles, which are positively charged, are attracted to the negatively charged plate.
2. **Beta particles** (green vector): These particles are deflected downward towards a labeled "Positive plate." Since beta particles are negatively charged, they are attracted to the positively charged plate.
3. **Gamma rays** (yellow vector): These are indicated to travel in a straight line, unaffected by the electric field, symbolizing their neutral charge.

The diagram visually represents how particles with different charges behave when subjected to an electric field, illustrating the forces on charged particles.

[Generated by AI]

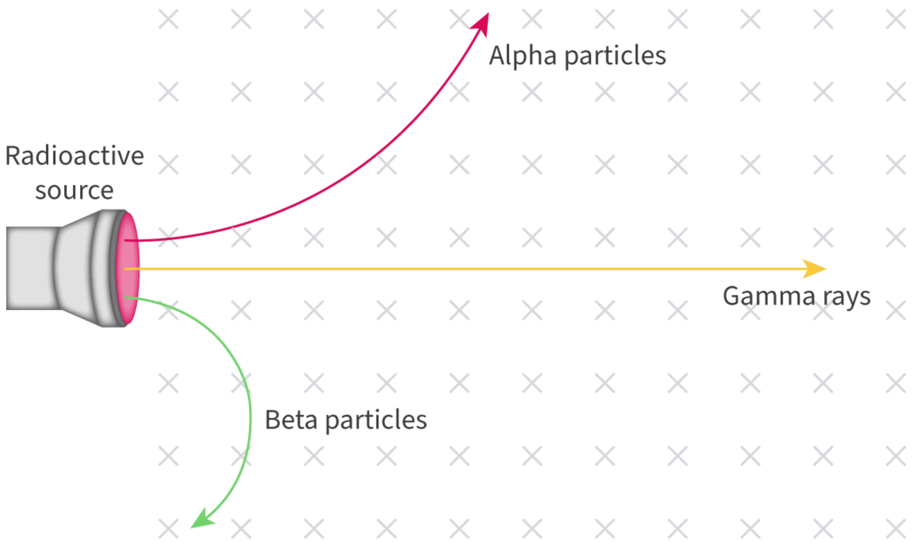

Figure 4b. The paths of alpha particles, beta-minus particles in a uniform magnetic field.

More information for figure 4

The diagram illustrates the paths of various particles emitted from a radioactive source in a uniform magnetic field, depicted by spaced 'X' marks suggesting the field's direction and strength.

- A radioactive source is shown on the left emitting particles.
- The path of alpha particles is represented by a magenta curved arrow bending upwards and arcing to the left, indicating they are deflected by the magnetic field.
- Beta particles follow a green curved path bending downwards to the right, suggesting a different deflection due to their lighter mass and opposite charge to alpha particles.
- Gamma rays are represented by a straight orange line, continuing directly in the initial direction to the right, unaffected by the magnetic field as they are electrically neutral.

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- Labels identify 'Alpha particles', 'Beta particles', and 'Gamma rays' along their respective paths, and the 'Radioactive source' is identified near the origin of the paths.

[Generated by AI]

Ionising ability of nuclear radiation

The energies of alpha particles, beta particles and gamma rays are often described using the kiloelectronvolt (keV), equivalent to one thousand eV, or the megaelectronvolt (MeV), equivalent to one million eV.

Individual radioactive decays typically release energies ranging from a few keV to a few MeV.

Making connections

The electronvolt (eV) is a unit of energy used to express electron transition energies in atoms (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-431911/)). One eV is equivalent to 1.60×10^{-19} joules (J).

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/radioactive-decay-id-46542/print/) Assign

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

It is possible for an atom to lose or gain one or more of its electrons, in a process called ionisation. An atom that has been ionised and does not have the same number of electrons as protons is called an ion.

As a result of the energy they carry, alpha particles, beta particles and gamma rays all cause ionisation of atoms and can be described as ionising radiation.

Worked example 1

An alpha particle is emitted with an energy of 5.0 MeV and travels through the air. It loses approximately 36 eV each time it causes an ionisation.

1. Assume that all of the alpha particle's energy is used to ionise the air molecules. How many ionisations does the alpha particle cause?
2. If the alpha particle travels 3.0 cm in air before losing all its energy, how many ionisations does it cause per millimetre travelled?

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1. $5.0\ \text{MeV} = 5.0 \times 10^6\ \text{eV}$

$$\frac{(5.0\times10^6)}{36} = 1.38\times10^5$$
$$= 1.4\times10^5\ (2\ \text{s.f.})\ \text{ionisations}$$

2. $3.0\ \text{cm} = 30\ \text{mm}$

$$\frac{1.38\times10^5}{30} = 4.62\times10^3$$
$$= 4600\ (2\ \text{s.f.})\ \text{ionisations}$$

As you can see from **Worked example 1**, even a single alpha particle has enough energy to ionise many atoms. Each ionisation event produces a positive ion that has lost an electron, and a negative ion that has gained that electron.

Making connections

In the experiment that led to the discovery of the atomic nucleus, scientists Geiger and Marsden used a screen to detect alpha particles. A barely visible flash of light was created each time an alpha particle hit the screen. This is because alpha particles carry energy that excites electrons in the atoms of the screen's coating. Light is emitted when the electrons return to lower energy states (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).

Video 2 explains why alpha particles, beta particles and gamma rays have different ionising abilities.

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Video 2. The ionising abilities of alpha particles, beta particles and gamma rays.

The penetrating abilities of alpha particles, beta particles and gamma rays are affected by their ionising abilities. The more ionisations a particle causes per unit distance travelled, the shorter its path before it loses all its energy.

Alpha particles create many more ions per unit distance than beta particles or gamma rays. As a result, alpha particles generally have the shortest path and gamma rays the longest path in any given material.

Table 2 summarises the properties of alpha particles, beta particles and gamma rays.

Table 2. Properties of alpha particles, beta particles and gamma rays.

Radiation type	Relative ionising ability	Relative penetrating ability	Charge	Mass (kg)	Speed (in terms of light speed *c*)
alpha particle	greatest	least	+2e	6.64×10^{-27}	typically 0.05–0.07*c* when first emitted
beta particle	intermediate	intermediate	—1e	9.1×10^{-31} $(\approx \frac{1}{8000} \times \alpha)$	typically 0.3–0.99 *c* when first emitted
gamma ray	least	greatest	0	0	c

Dangers of ionisation

Ionisation can harm living organisms by damaging or destroying their cells. If exposure is high enough, this can cause serious illness or death. Lower levels of exposure can cause damage that is not immediately obvious but increases the probability of cancer developing in the future.

Although gamma rays are the least ionising type of nuclear radiation, they are not low-risk. They cause the lowest number of ionisations per millimetre but they can travel right through a living organism, causing ionisation along their path. The total damage by many gamma rays can be severe.

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Video 3. Is radiation dangerous?

International Mindedness

Many warning signs, such as traffic signs, vary between countries, but the radiation sign (A) is an international hazard symbol that is used all over the world.

The radiation sign (B) was launched by the International Atomic Energy Agency in 2007. It is displayed inside equipment that contains a powerful source of ionising radiation. It aims to deter people from disassembling the equipment, and to warn them to move away if the interior becomes exposed.

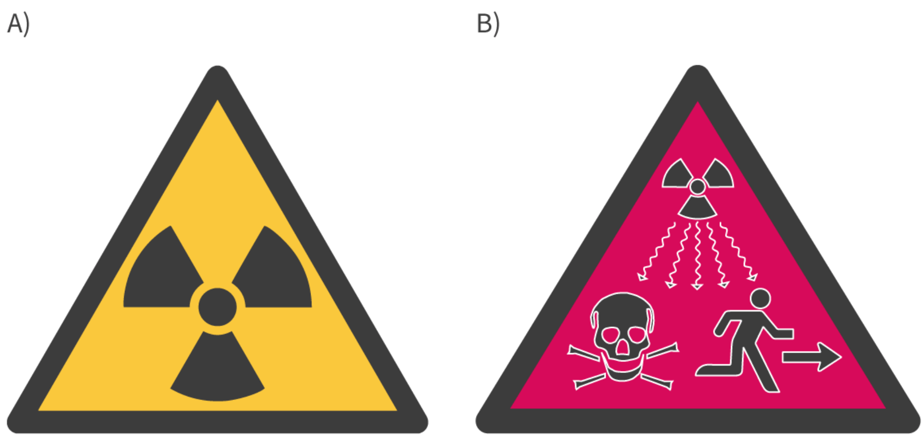

Figure 6. The international symbol warning of potential nuclear radiation exposure (A) and the ionising radiation warning symbol for use inside equipment containing a radioactive source (B).

More information for figure 6

The image displays two triangular radiation warning symbols.

A) On the left, a yellow triangle contains a black trefoil radiation symbol, consisting of three blades surrounding a central circle, indicating a warning for potential nuclear radiation exposure.

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B) On the right, a magenta triangle shows a more complex icon used within equipment containing radioactive sources. The top of the triangle features a black trefoil symbol with downward-pointing arrows suggesting radiation emission. Below, a white skull and crossbones are centered to signify danger. To the right, a white figure is shown running towards an arrow, indicating the need to evacuate or move away if exposed to radiation.

[Generated by AI]

Can you create a radiation hazard symbol that would be easy to understand all over the world?

We need to take precautions when working with radioactive sources. There are three ways we can protect ourselves and others:

- Minimise the time spent working with the source.
- Maximise the distance between ourselves (and others) and the source.
- Use shielding.

All of these precautions help to minimise exposure to ionising radiation.

Sort the precautions in **Interactive 1** into the correct columns of the table to show whether they minimise time, maximise distance or use shielding.

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Interactive 1. Safety Precautions When Working With Radioactive Sources.

Creativity, activity, service

Strand: Service
Learning outcome: Demonstrate the skills and recognise the benefits of working collaboratively

Fresh foods such as tomatoes, mushrooms and berries may have microorganisms such as bacteria on their surface. To extend the lifetime of the food, it can be sterilised using gamma rays to destroy many or all of the microorganisms. This process is called irradiation.

A common misconception about the irradiation of food is that it makes the food radioactive. Research irradiation and create a short blog post (about a page) or a two to three minute video to help the general public understand whether irradiated food is safe. Your resource should include an explanation of the difference between irradiation and contamination.

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Work through the activity to check your understanding of the penetrating ability and ionisation ability of nuclear radiation.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

The different penetrating and ionising abilities of alpha particles, beta particles and gamma rays means they have different uses. Look at each application of nuclear radiation and decide whether a source of alpha particles, beta particles and gamma rays is most suitable.

1. A factory makes paper in long sheets that are then cut into smaller pieces. The thickness of the paper must be continually checked so the machinery can be adjusted if it is making the paper too thick or too thin. A radioactive source is positioned on one side of the sheet and a detector on the other side. The detected count rate is used to monitor the paper thickness.
2. To observe whether a person's kidneys are functioning normally, a radioactive tracer (chemical compound with radioactive atoms) is injected into the person's blood. The kidneys filter the tracer out of the blood. A special camera, placed outside the body, makes an image of the kidneys. The camera measures the variations in intensity of nuclear radiation coming from the kidneys. If part of a kidney is not functioning correctly, this may cause a lack or a buildup of the tracer, and that area will appear darker or lighter than normal in the image.
3. In radiotherapy, nuclear radiation is used to destroy cancerous cells in a brain tumour. Radiation is directed towards the tumour from different directions in multiple beams. Damage to healthy cells needs to be minimised.
4. Nuclear radiation can be used to find leaks in underground pipes carrying liquids. A tracer is introduced into the liquid. A Geiger counter is used to measure count rates above ground along the route of the pipe. If the count rate is higher in one area, this indicates the liquid is leaking out of the pipe into the soil, carrying the radioactive material with it.
5. Some smoke alarms contain an electric circuit with a break in it. The air in this gap does usually conduct well enough to complete the circuit, but a radioactive source positioned in or near the gap causes ionisation of air molecules. Since ions are charged, they make the air conduct, which allows a current to flow across the gap. If smoke gets into the alarm, ions become attached to the smoke particles. The charged smoke particles move much more slowly than the free ions, so the current in the circuit decreases. This triggers an alarm.

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1. Source of beta particles

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Alpha particles are typically stopped by a sheet of paper, so the alpha count rate will remain at or very close to zero for any thickness of paper.

Gamma rays are highly penetrating and are hardly affected by a sheet of paper, so the gamma count rate will not change much when the paper thickness changes. Since gamma rays can travel long distances through air and other substances, factory workers could be exposed to the radiation.

Beta particles have a penetration that is between that of alpha particles and gamma rays, and they are partly stopped by paper. Changes in paper thickness affect how many beta particles pass through, and the varying count rate measurements can be used to adjust the machinery and stop the paper from becoming too thick or thin.

2. Source of gamma rays

   Alpha particles are not penetrating enough to travel from the kidney to the outside of the body. Also, an alpha source could cause a lot of damage while travelling around the body and then passing through the kidneys, because the emitted alpha particles are highly ionising.

   Most beta particles will not penetrate from the kidney to the outside of the body. Beta particles are moderately ionising, and so a beta source inside the body could cause considerable damage while travelling around the body.

   A gamma source is the most suitable, because gamma rays are penetrating enough to travel from the kidneys to the camera. Gamma rays cause the least ionisation as they pass through the body.

3. Source of gamma rays

   Alpha particles are not penetrating enough to pass through the skin.

   Beta particles can penetrate a few millimetres of skin but will cause significant damage to healthy cells along their path. They will not typically pass through the skull or deep into the brain.

   Gamma rays are most appropriate as they can penetrate to the tumour. As many as 200 low-intensity beams converge on the tumour from different directions. Only the tumour receives the full dose, while healthy tissue receives very low doses.

4. Source of gamma rays

   Alpha particles are very unlikely to penetrate far enough, through ground and air, to reach the detector.

   Beta particles will not usually penetrate far enough through the ground around the leak to cause a significantly increased count rate at the surface.

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Gamma rays are often used because they partially penetrate a thick layer of soil or other material above the pipe. Where there is no leak, there will usually still be a detectable count rate from the tracer, but where the liquid has leaked and spread out, the count rate will be higher as some of the tracer is carried closer to the surface.

5. Source of alpha particles

Gamma rays are very penetrating and would easily pass through the casing of the smoke alarm, posing a health risk to people nearby. Gamma rays are also the least ionising, and may not cause enough ionisation to allow a measurable current to flow.

Some beta particles may pass through the casing of the smoke detector and pose a health risk to people. There could also be a considerable risk to anyone who opened up the casing of the detector, for example, to change a battery.

Alpha particles are the least penetrating and are stopped by even a thin barrier such as paper. They do not penetrate the outer parts of the smoke alarm, so do not put people at risk.

5 section questions

Question 1 SL HL Difficulty:

Which statements are correct?

1. Alpha particles are no longer a health risk after they have lost all their energy.
2. A gamma source is a risk to health when it is inside the body but not when it is outside the body.
3. Beta-minus particles are typically less penetrating than alpha particles and more penetrating than gamma rays.

1 1 only ✓

2 3 only

3 1 and 2

4 2 and 3

Explanation
Alpha particles can only cause harm because they have enough energy to cause significant ionisation, which can damage cells. After they have lost their energy, alpha particles no longer pose a risk to health.

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Gamma rays can penetrate right through the body and cause ionisation, so a gamma source poses a similar risk to health whether it is outside or inside the body.

Beta-minus particles are typically more penetrating than alpha particles and less penetrating than gamma rays.

Question 2

SL HL Difficulty:

Why can beta-minus particles harm a living organism?

1 They are energetic ✓

2 They are poisonous

3 They stick to living cells

4 They make an organism negatively charged

Explanation

Beta-minus particles are electrons. Electrons are not dangerous when they are not fast-moving. Beta-minus particles are harmful because they are electrons with energy. Because of their energy, beta-minus particles can ionise atoms, which can damage living cells.

Question 3

SL HL Difficulty:

Count rates are measured at a fixed distance from a radioactive source, with different barriers between the source and the detector.

The table shows count rates after correcting for background radiation.

Barrier	Background-corrected count rate (counts/min)
none	1206
sheet of paper	864
5 mm aluminium	839

Which type(s) of nuclear radiation does the source emit?

1 alpha particles and gamma rays ✓

2 beta particles only

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3 alpha particles and beta particles

4 beta particles and gamma rays

Explanation

The significant reduction in count rate by a piece of paper indicates that the source emits alpha particles.

The radiation that passes through the paper and through the aluminium is unlikely to be beta particles. Beta particles would be mostly stopped or significantly reduced by 5 mm of aluminium, whereas gamma rays would not. Therefore, the source also emits gamma rays.

Question 4

SL HL Difficulty:

A Geiger counter measures the average count rate at a fixed distance from a radioactive source. This is 120 counts per second. A sheet of paper is placed between the source and the counter. The average count rate is now 20 counts per second. When the paper is removed, the average count rate returns to 120 counts per second.

Which of the following could be the average background count rate?

1. 10 counts per second
2. 20 counts per second
3. 100 counts per second

1 1 and 2 ✓

2 1 only

3 2 only

4 2 and 3

Explanation

If the source emits alpha particles only, then the paper is likely to block all of them. In this case, the average rate of 20 counts per second with the paper in place is caused by background radiation. Then the average background count rate is 20.

If the source emits gamma rays as well as alpha particles (or if the paper is very thin or the alpha particles have a lot of energy), then some radiation from the source may reach the Geiger counter even with the paper in place. In this case, the average background radiation is less than 20 counts per second. It is possible that it is 10 counts per second.

The average background radiation count rate cannot be higher than 20 counts per second. If it were 100 counts per second, then the average count rate with the paper in place would be at least 100.

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Question 5

SL HL Difficulty:

A scientist works with radioactive sources in a lab. They wear protective gloves and hold sources with tongs. One day, the scientist briefly holds a radioactive source in their hands, without wearing gloves. The source emits alpha particles and gamma rays. The scientist picks up an apple and eats it without washing their hands. This poses a health risk.

Which row in the table shows the type of radiation which is the greater risk and the correct reason for the risk?

	Type of radiation	Reason
A	alpha particles	Small amounts of the radioactive source may stick to the scientist's hands.
B	alpha particles	When the scientist's hands are exposed to the radiation, it makes the outer layers of their skin radioactive.
C	gamma rays	Small amounts of the radioactive source may stick to the scientist's hands.
D	gamma rays	When the scientist's hands are exposed to the radiation, it makes the outer layers of their skin radioactive.

1 A ✓

2 B

3 C

4 D

Explanation

Alpha particles are highly ionising, so even very small amounts of an alpha source in the body can cause significant damage to tissues that it comes close to (such as parts of the throat or stomach).

Gamma rays are not highly ionising. So alpha particles pose the greater risk.

If some of the radioactive source, even in amounts too small to see, sticks to the skin, then that poses a risk. When the scientist picks up the apple, some of the source might stick to the apple and be swallowed. An object does not become radioactive by exposure to alpha particles or gamma rays, so the scientist's hands do not become radioactive.

Student view

Half-life

Learning outcomes

By the end of this section you should be able to:

- Explain that radioactive decay is random and spontaneous.
- Describe half-life and use values of half-life to describe the changes in activity and count rate during radioactive decay.

Large pieces of a wooden sculpture that appear to represent a human, known as the Shigir Idol, were discovered in a peat bog in Russia in 1890 (**Figure 1**). Its age has been measured as about 12 000 years old.

Figure 1. Part of the Shigir Idol.

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The age of the sculpture was measured using carbon dating, a technique that involves measuring the radioactivity of the object. How can radioactivity tell us the age of an object?

The nature of radioactive decay

It is not possible to predict when any individual nucleus will decay. Radioactive decay is random.

Physicist Marie Skłodowska-Curie and others investigated whether it was possible to make radioactive decay speed up or slow down. Their experiments included subjecting radioactive sources to a wide range of temperatures and pressures. These changes had no effect on the rate of decay, and no external factor has ever been found that affects the rate of decay.

Radioactive decay is spontaneous. There is no apparent trigger or cause that makes any individual nucleus decay at a particular time.

Half-life and activity

For a sample of a radioactive isotope that decays into a stable isotope, the number of decays per unit time, or activity, decreases over time. The unit for activity is the becquerel (Bq), where 1 Bq equals 1 decay per second.

As time passes, there are fewer nuclei remaining that have not yet decayed. After enough time has passed (which may be a very long time indeed), there will be no nuclei left to decay and the activity will be zero.

The half-life is the amount of time it takes for half the nuclei in a sample to decay. It can be represented by the symbol $t_{\frac{1}{2}}$.

Use this simulation (https://phet.colorado.edu/sims/cheerpj/nuclear-physics/latest/nuclear-physics.html?simulation=alpha-decay) to explore the alpha decay of polonium-211 nuclei into lead-207 nuclei. The half-life is 0.5 s.

Select the 'Multiple Atoms' tab. (The 'Single Atom' tab is beyond the scope of the DP physics course.) Add nuclei by clicking on 'Add 10'. Click this a few times. At the top of the screen, you can see the nuclei moving along a time axis. When a nucleus decays, it stops moving along the axis, and falls down. The time at which it stops shows how long it lasted before decaying. You can also see an animated pie chart at the top left which shows how many nuclei have decayed and how many have not yet decayed.

Student view

Do half of the nuclei decay during one half-life? Is this always exactly true, or only approximately true?

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In **Interactive 1**, you can see a model of the radioactive decay of 1000 unstable nuclei into stable nuclei. Each nucleus is represented by a circle, which changes colour when the nucleus decays. The graph records the number of undecayed nuclei remaining, at intervals of one day. Use the ‘Forward 1 day’ and ‘Backward 1 day’ buttons to move forwards or backwards in time.

Interactive 1. Half-life simulation.

More information for interactive 1

The simulation visually represents the radioactive decay of 1000 unstable nuclei over time. Each nucleus is depicted as a small circle, initially all in the same state, indicating that they are undecayed. As time progresses, some nuclei randomly change color to signify decay into stable nuclei.

A graph on the screen continuously tracks the number of undecayed nuclei, updating at one-day intervals. The x-axis represents time in days, advancing in regular intervals, while the y-axis represents the number of undecayed nuclei remaining. Initially, the count starts at 1000 and decreases as nuclei decay.

As decay progresses, the curve follows an exponential pattern, steep at first and gradually flattening. This shape reflects the characteristic half-life behavior, where the number of undecayed nuclei decreases by roughly half over consistent time intervals. The graph provides a smooth, general trend rather than an exact stepwise reduction, emphasizing the probabilistic nature of decay. The user can interact with the simulation using "Forward 1 day" and "Backward 1 day" buttons, allowing stepwise navigation through the decay process.

Each day, some nuclei decay, and the simulation updates to show how many nuclei remain undecayed and how many have decayed. The user can also start a new simulation to reset the system.

Student view

In the example shown in the interactive, at Day 0, there are 1000 undecayed nuclei. After one day, the simulation shows that

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870 nuclei remain undecayed, and 129 have decayed. By Day 2, 757 nuclei remain, and 242 have decayed. As the simulation continues, the number of undecayed nuclei decreases, and the number of decayed nuclei increases. This provides a clear representation of the process of radioactive decay.

To calculate the number of decayed nuclei, subtract the number of undecayed nuclei from the initial total. For example, at Day 1, the number of decayed nuclei is calculated as $1000 - 870 = 129$. Similarly, at Day 2, $1000 - 757 = 242$ nuclei have decayed.

This interactive tool provides a hands-on way to understand the process of radioactive decay. It allows users to experiment with the time progression and see the decay unfold in real-time, offering an intuitive approach to learning about radioactive materials and the concept of decay rates. By interacting with the simulation, users can gain a deeper understanding of how radioactive decay occurs over time and the significance of concepts such as half-life and decay rates.

If you run the simulation in **Interactive 1** more than once, you will find that you do not get exactly the same results each time. That is because each nucleus has been programmed to have a probability of decay in each time interval, to reflect the random nature of radioactive decay.

For any radioactive nucleus that decays into a stable nucleus, a graph of activity against time has a very similar shape to the graph in **Interactive 1**.

Figure 2 shows a theoretical example.

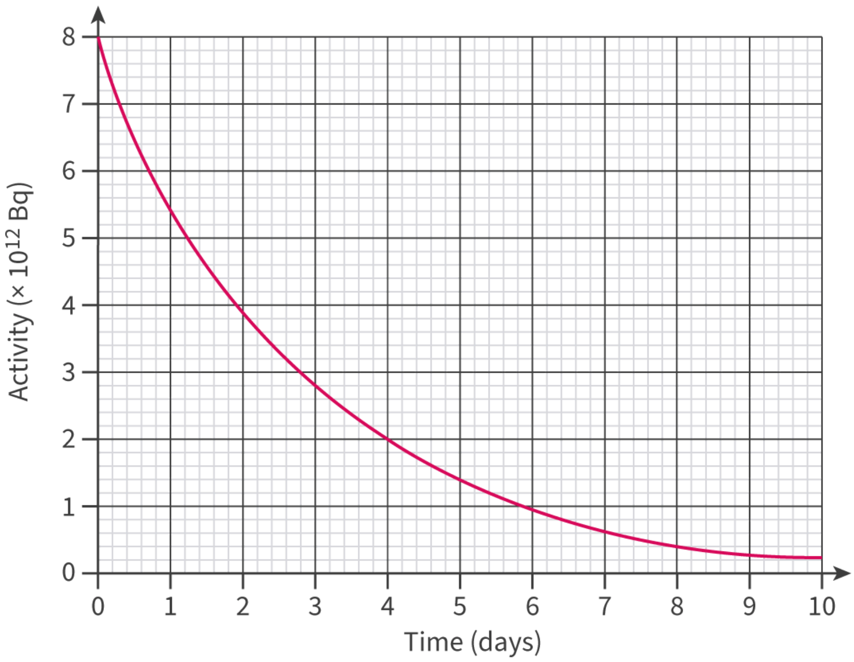

Figure 2. A graph of activity against time for a radioactive nucleus that decays into a stable nucleus.

More information for figure 2

The image is a graph displaying the relationship between activity and time for a radioactive decay process. The X-axis represents time in days, ranging from 0 to 10. The Y-axis represents activity measured in units of 10^12 Becquerels, ranging from 0 to 8. The data curve shows an exponential decrease in activity over time, illustrating the concept of radioactive decay.

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view

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As time increases, activity decreases rapidly, displaying a typical decay curve with a half-life indicating the time taken for the activity to reduce to half its initial value.

[Generated by AI]

The relationship between activity and time can be described using a mathematical function called exponential decay (see section E.3.6 (/study/app/physics/sid-423-cid-762593/book/radioactive-decay-law-hl-id-46548/)). This gives the activity an important property – it always takes the same amount of time to halve. This time interval is the half-life of the nucleus. (The half-life remains constant and predictable as long as there is a large enough number of nuclei – which is the case in every situation you are likely to encounter.)

The half-life can be estimated from the graph in **Figure 2** by choosing a time, reading the count rate at that time, and then reading how long it takes for the count rate to fall to half of that value.

Worked example 1

The graph in **Figure 2** represents the activity of a nuclide over time.

Determine the half-life of the nuclide.

At day 0, activity = 8.0×10^{12} Bq

At day 2, activity = 4.0×10^{12} Bq

Half-life = 2.0 days

At day 4, activity = 2.0×10^{12} Bq

At day 6, activity = 1.0×10^{12} Bq

Half-life = 2.0 days

The half-life is not affected by:

- the initial amount of the radioactive nuclide.
- the time at which we start to determine the half-life.

Student
view

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Interactive 2 shows a graph of the activity of a radioactive sample against time. Drag the point labelled ‘Start measurement here’ to choose a starting time for a half-life measurement. Then move the ‘Measure half-life’ slider to the right. This shows the half-life as measured from the start of the graph, and then the half-life as measured from your chosen starting time. Compare the results. Are they the same?

Move the ‘Initial activity’ point up or down to change the activity at the start time. Does this affect the half-life? Try changing the half-life. How does this affect the graph?

Interactive 2. A graphical simulation of exponential decay.

More information for interactive 2

This simulation models the radioactive decay activity of a sample over time using a graph. The x-axis represents time, while the y-axis represents activity, which measures the rate at which the sample undergoes decay. The graph follows an exponential decay curve, indicating a decreasing activity level as time progresses.

A draggable point labeled "Start measurement here" allows users to select a starting time on the graph. Once set, a "Measure half-life" slider is moved to the right, displaying two half-life measurements, one measured from the start of the graph and the other one measured from the newly chosen start time. The results show that the half-life remains constant, regardless of when the measurement begins. This demonstrates that radioactive decay is independent of past history; it always follows the same half-life pattern.

A point labeled "Initial activity" can be moved up or down, adjusting the starting activity. Despite changing the initial value, the half-life remains unchanged. This highlights that half-life depends only on the radioactive substance's properties, not on its starting activity.

Student view

A separate control allows the half-life to be adjusted. Increasing the half-life makes the decay curve less steep, meaning the activity declines more slowly. Decreasing the half-life makes the decay curve steeper, meaning the activity decreases more quickly. This visually confirms the relationship between half-life and decay rate: a longer half-life means slower decay, while a shorter half-life means faster decay.

Through this interactive users will understand that half-life is constant, regardless of when it is measured, the initial activity changes do not affect the half-life, adjusting the half-life changes how quickly the activity decreases over time and, radioactive decay follows an exponential pattern and is probabilistic in nature.

Work through the activity to explore radioactive decay.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

You are going to carry out a simulation of radioactive decay. You will need at least 50 coins or 6-sided dice. You will also need a shallow box to throw the coins or dice into.

Each throw represents the passing of a unit of time. A dice ‘decays’ when it lands on a 6 and a coin ‘decays’ when it lands on a ‘head’.

After each throw, remove all ‘decayed nuclei’ before throwing again. Continue until all or most of the nuclei have decayed.

Create a suitable table and graph so that you can measure the half-life of the ‘nuclide’.

Discuss the questions below with your partner or in a small group.

1. How does the experiment simulate the randomness of radioactive decay?
2. What is the measured half-life of your nuclide?
3. The behaviour of the item is random, yet the overall behaviour is to some extent predictable. Discuss this idea.
4. If you had 1000 items, how would that affect the reliability of the half-life measurement?
5. One milligram of radium-226 contains over 2×10^{18} atoms. How do you think such a large number of atoms affects the reliability of half-life measurements?
6. Why do you think we use the quantity half-life and not ‘whole-life’ for radioactive sources?

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7. The experiment is intended to model the mathematics of radioactive decay. Can you think of any flaws in the model?

Concept

Half-lives of radioactive nuclides vary tremendously. For example, the half-lives of naturally-occurring francium-223 and thorium-232 are 22 minutes and 14 billion years (roughly the age of the Universe), respectively. The half-lives of artificially created nuclides can be less than a nanosecond. How is it possible for a nuclide with a half-life of only 22 minutes to exist naturally on Earth?

To predict the activity A of a radioactive sample after n half-lives, halve the initial activity (A_0) n times. If you are given the half-life $t_{\frac{1}{2}}$ and the time t that passes, you will first need to work out how many half-lives t equals. This can be written formally as:

$$A = A_0 \times \left(\frac{1}{2}\right)^n \quad \text{where } n = \text{number of half-lives } = \frac{t}{t_{\frac{1}{2}}}$$

Similarly, the count rate C after time t can be written

$$C = C_0 \times \left(\frac{1}{2}\right)^n$$

and the number of undecayed nuclei after time t can be written

$$N = N_0 \times \left(\frac{1}{2}\right)^n$$

If you are studying the HL course, you are also expected to calculate A, C and N after an amount of time that is not a whole number of half-lives (see section E.3.6 (/study/app/physics/sid-423-cid-762593/book/radioactive-decay-law-hl-id-46548/)).

Worked example 2

The activity of a radioactive sample is 7.5×10^{16} Bq.

The sample contains a radioactive nuclide with a half-life of 3.0 hours, which decays into a stable nuclide.

Student view

Predict the activity of the sample after 9.0 hours.

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Solution steps	Calculations
Step 1: Work out how many half-lives equal 9.0 hours.	$\text{Number of half-lives} = \frac{9.0}{3.0}$ $= 3$
Step 2: For each half-life that passes, halve the activity (either using the formula or simply by halving the initial activity three times).	$A = A_0 \times \left(\frac{1}{2}\right)^n \quad \text{where } n = \text{number of half-lives} = \frac{t}{t_{\frac{1}{2}}}$ $= 7.5 \times 10^{16} \times \left(\frac{1}{2}\right)^3$ $= 9.375 \times 10^{15}$ $= 9.4 \times 10^{15}\ \text{Bq (2 s.f.)}$

Exercise 1

Click a question to answer

Half-life and count rate

To measure the activity of a source, a detector would need to be 100% sensitive and detect nuclear radiation emitted by the source in every direction. In reality, detectors only measure a fraction of the emitted radiation. The number of detections per unit time is the count rate (see section E.3.2 (/study/app/physics/sid-423-cid-762593/book/nuclear-radiation-id-46543/)). The count rate is affected by the size and sensitivity of the detector and by its distance from the source.

Count rates that are measured using a consistent method are directly proportional to the activity of the source. A graph of count rate against time has the same shape as a graph of activity against time and can also be used to determine half-life.

Figure 3 shows count rate measurements for a sample of a radioactive isotope of vanadium $\left({}^{48}_{23}\text{V}\right)$ that decays into a stable isotope of titanium. The measurements are background-corrected – the average background count rate has been subtracted from the source count rate.

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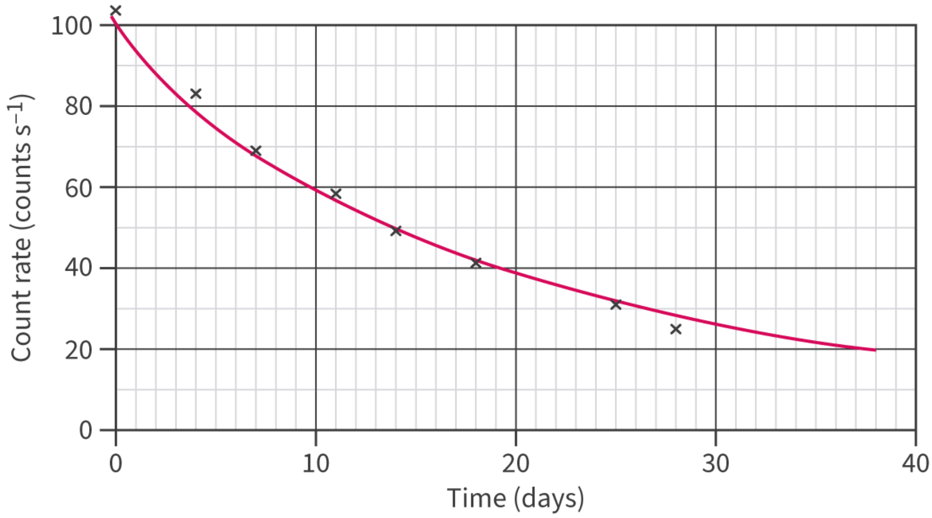

Figure 3. A graph of background-corrected count rate measurements of a radioactive source.

More information for figure 3

The image is a graph illustrating the count rate, measured in counts per second, against time in days. The X-axis represents time ranging from 0 to 40 days, with labels at every 10-day interval. The Y-axis represents the count rate, ranging from 0 to 100 counts per second, with labels at every 20 counts.

The graph displays a series of plotted points as 'X' marks, representing the actual count rate measurements over the given time period. A red curve of best fit, drawn through these points, demonstrates an overall downward trend, indicating a decay pattern.

The trend line starts at approximately 100 counts per second at day 0 and gradually decreases to about 20 counts per second by day 40. This decreasing trend highlights the radioactive decay of the vanadium isotope as it transitions to a stable isotope of titanium. It is noted that while some data points align closely with the best-fit curve, others vary slightly, suggesting fluctuations in the count rate measurements related to background and source variations.

[Generated by AI]

A curve of best fit has been drawn for the graph in **Figure 3**. Note that the count rate measurements do not all lie on the curve. An average background count rate has been subtracted from the source count rate, but the background count rate is not constant. The source count rate also has random variations, and these are more significant at lower count rates.

For a graph with a curve of best fit, estimating the half-life three times and taking the mean is likely to give a more accurate result than a single half-life estimate (**Figure 4**).

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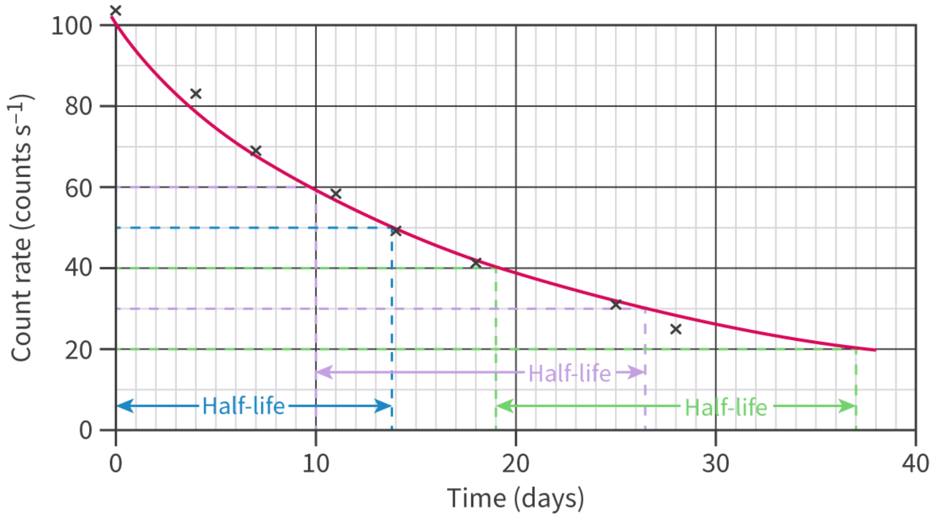

Figure 4. Estimating half-life from a graph of background-corrected count rate of a radioactive source.

More information for figure 4

The image is a graph depicting the radioactive decay of a substance over time. The X-axis represents time in days, ranging from 0 to 40. The Y-axis represents the count rate, labeled as counts per second, and ranges from 0 to 100.

A red curve shows the decay of the radioactive source, starting at a count rate of 100 and decreasing over time. The graph includes three highlighted segments representing the half-life estimations. These are marked with horizontal and vertical arrows labeled 'Half-life' at three intervals showing the time it takes for the count rate to decrease to half its previous value.

The graphical data points are marked along the curve, illustrating the decline in count rate. The curve follows a downward exponential trend as expected in radioactive decay, representing a gradual reduction of count rate with increasing time. The graph has grid lines to assist in identifying precise values of count rate at different times.

[Generated by AI]

The three half-live estimates from the graph in **Figure 4** are 13.6 days, 16.2 days and 18.0 days.

The measured half-life is the mean, with uncertainty equal to half of the range of the measurements (where the range is 18.0 − 13.6 = 4.4 days). This is 16 ± 2 days.

Exercise 2

Click a question to answer

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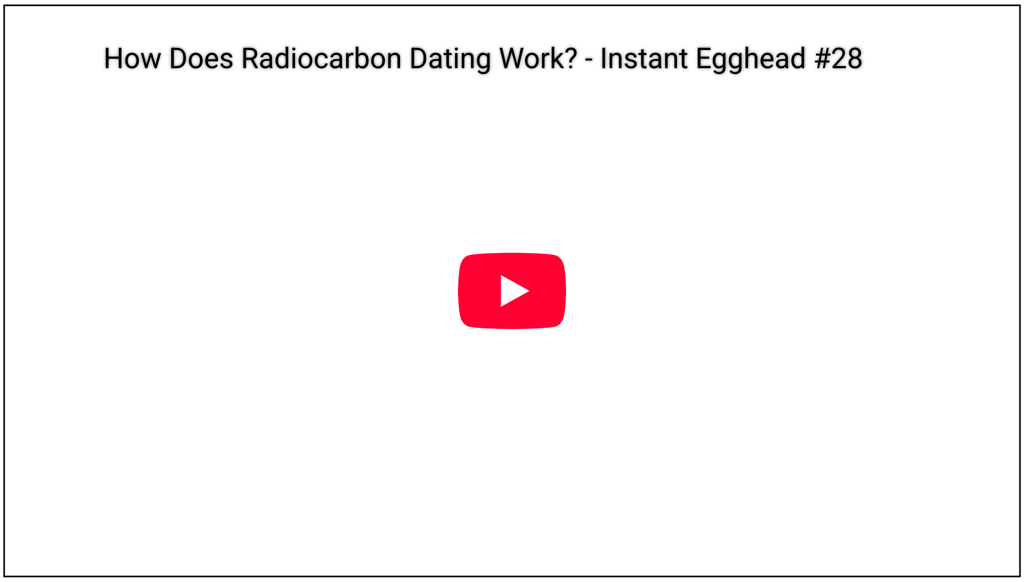
Creativity, activity, service

Strand: Creativity
Learning outcome: Demonstrate that challenges have been undertaken, developing new skills in the process.

Some physics departments and research labs have an artist in residence, who creates pieces inspired by the scientific research. Textile artist Lindsay Olson (https://www.textileartist.org/lindsay-olson-art-physics-and-the-elegant-universe/) was artist in residence at Fermilab, a particle physics laboratory in the USA.

Create a piece of art that is inspired by something you have learned about radioactivity, such as the spontaneous nature of radioactive decay, or that the random behaviour of individual nuclei leads to predictable behaviour at a larger scale. It could be a piece of visual art, music, dance, poetry, or another form of creative expression. Can you share your art with others to inspire interest in this area of physics?

A technique called radioactive dating can be used to measure the ages of certain types of object by measuring their activities. This makes use of the fact that the activity of an isotope sample decreases over time. Watch **Video 1**, which shows how one type of radioactive dating called carbon dating works. In the activity in the next section you will learn more about radioactive dating.



Video 1. How does radiocarbon dating work?

5 section questions

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view

Question 1

SL HL Difficulty:

Which is a correct definition of the half-life of a pure sample of a radioactive nuclide?

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1. The time taken for the activity of the sample to halve.
2. Half of the time taken for the activity of the sample to fall to zero.
3. The time taken for the background-corrected count rate from the sample to halve.
4. Half of the time taken for all the nuclei in the sample to decay.

1 1 and 3 ✓

2 2 and 4

3 2, 3 and 4

4 1, 2, 3 and 4

Explanation

The half-life is the time taken for the activity of a sample to halve.

The background-corrected count rate is proportional to the activity (as long as the count rate is measured in a consistent way). Therefore, the count rate takes the same time to halve as the activity.

The time taken for the activity to halve is not the same as half of the time taken for the activity to fall to zero. The time taken for the activity to fall to zero is unpredictable (and usually not possible to measure) since the activity is not over until the very last nucleus has decayed.

Question 2

SL HL Difficulty:

The background-corrected count rate measured for a radioactive nuclide falls from 160 counts s^{-1} to 5.0 counts s^{-1} in 12 hours.

What is the half-life of the nuclide?

Give your answer to an appropriate number of significant figures.

The half-life is 1 2.4 ✓ hours.

Accepted answers and explanation

#1 2.4

General explanation

A decrease in count rate from 160 counts s^{-1} to 5.0 counts s^{-1} occurs in 5 half-lives ($T_{\frac{1}{2}}$):

$$160 \text{ Bq} \xrightarrow{T_{\frac{1}{2}}} 80 \text{ Bq} \xrightarrow{T_{\frac{1}{2}}} 40 \text{ Bq} \xrightarrow{T_{\frac{1}{2}}} 20 \text{ Bq} \xrightarrow{T_{\frac{1}{2}}} 10 \text{ Bq} \xrightarrow{T_{\frac{1}{2}}} 5 \text{ Bq}$$

Student
view

12 hours is 5 half-lives.

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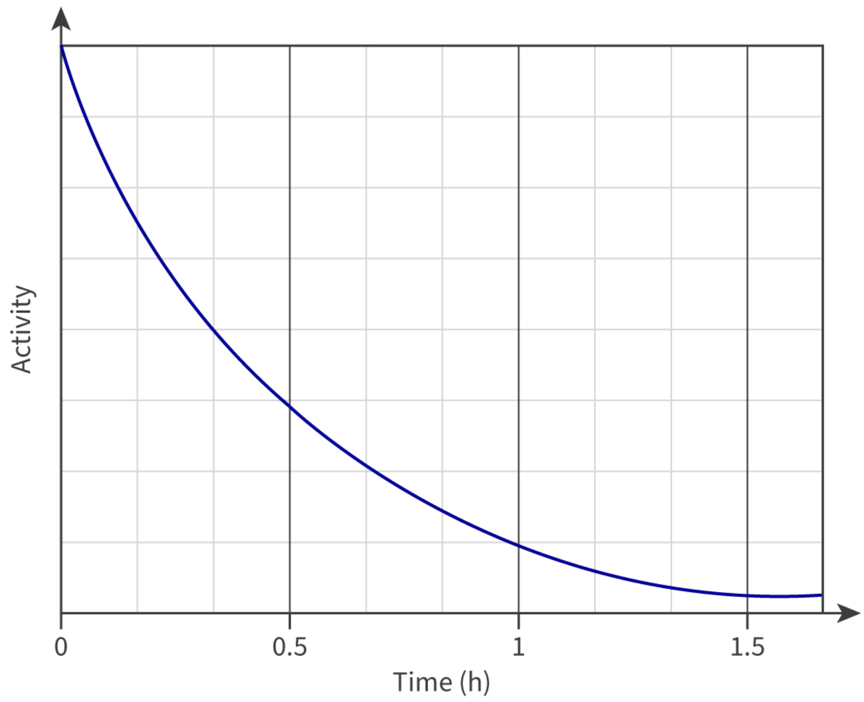
1 half-life is:

$$\frac{12}{5} = 2.4 \text{ hours (2 s.f.)}$$

Question 3

SL HL Difficulty:

The graph shows the activity of a radioactive nuclide as a function of time.



More information

How many minutes is the half-life of the nuclide?

The half-life is 1 20 ✓ minutes.

Accepted answers and explanation

#1 20

General explanation

The half-life is the time taken for the activity to halve. The initial activity is shown by eight divisions on the scale, and it halves to four in two time divisions.

Three time divisions represent 0.5 h, which is 30 minutes. So 2 time divisions represent 20 minutes, and the half-life is therefore 20 minutes.

Student view

Question 4

SL HL Difficulty:

A radioactive source contains a radioactive nuclide that decays into a stable nuclide.

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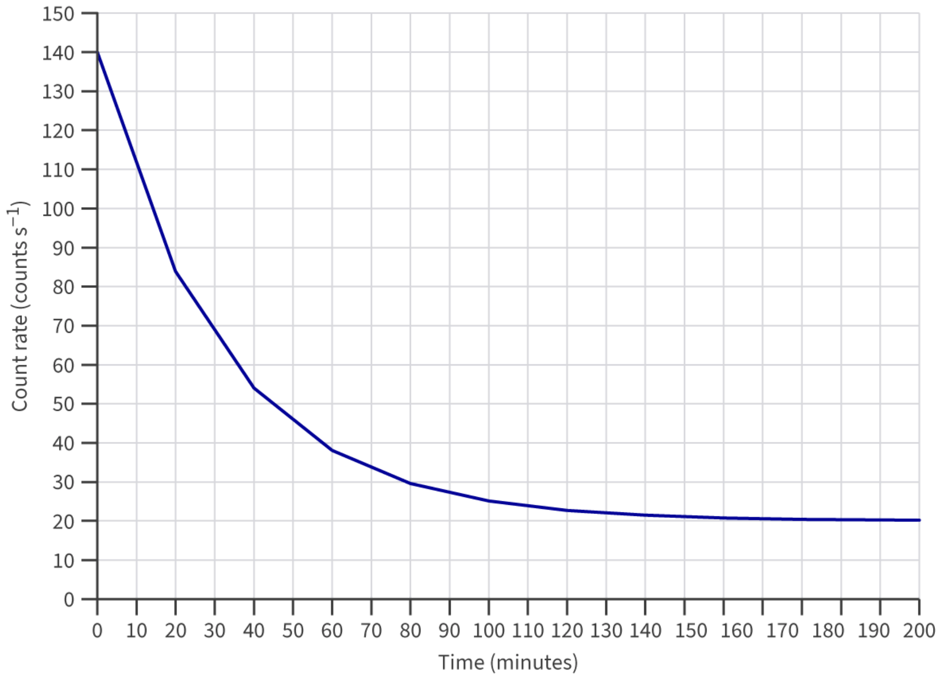
A Geiger counter is placed near the radioactive source and records a count rate for 200 minutes.

The graph shows the best fit curve of the results.



More information

What is the half-life of the nuclide?

Give your answer to 2 significant figures.

The half-life is 1 22 minutes.

Accepted answers and explanation

#1 22

General explanation

The count rate measurements have not been corrected for the background count rate. After about 180 minutes, the count rate reaches a value of 20 counts s^{-1}. This means that there is no measured count rate from the source. The background rate is 20 counts s^{-1}.

The initial count rate is 140 counts s^{-1}, so the initial count rate from the source is 120 counts s^{-1}. When this falls to 60 counts s^{-1}, the measured count rate is 80 counts s^{-1} because of the background count. The count rate is 80 counts s^{-1} at 22 minutes. The half-life is 22 minutes.

Student view

Question 5

SL HL Difficulty:

A sample of a fermium isotope is created artificially.

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The starting activity of the sample is 64 000 Bq.

The activity 12 days after the start is 4000 Bq.

Determine the activity 24 days after the start.

1 250 Bq ✓

2 500 Bq

3 1000 Bq

4 2000 Bq

Explanation

A decrease in activity from 64 000 Bq to 4000 Bq occurs in 4 half-lives $(T_{\frac{1}{2}})$:

$$64000 \xrightarrow{T_{\frac{1}{2}}} 32000 \xrightarrow{T_{\frac{1}{2}}} 16000 \xrightarrow{T_{\frac{1}{2}}} 8000 \xrightarrow{T_{\frac{1}{2}}} 4000$$

12 days is four half-lives.

24 days after the start, another four half-lives have passed.

The activity halves four more times:

$$4000 \xrightarrow{T_{\frac{1}{2}}} 2000 \xrightarrow{T_{\frac{1}{2}}} 1000 \xrightarrow{T_{\frac{1}{2}}} 500 \xrightarrow{T_{\frac{1}{2}}} 250$$

The activity after 24 days is 250 Bq (2 s.f.).

E. Nuclear and quantum physics / E.3 Radioactive decay

Activity: Half-life

E.3.11: Activity, count rate and half-life E.3.12: Changes in activity and count rate during decay

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Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:**
  - Thinking skills — Applying key ideas and facts in new contexts
  - Research skills — Using search engines and libraries effectively
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

Radioactive dating is a technique that uses half-life to determine the age of objects. You have already watched a video about carbon dating, which can be used to measure the age of materials that were once living, such as bone and wood. Research how uranium-238 is used in the dating of volcanic rocks. How is it similar to carbon dating? How is it different?

Now open the simulation.

1. Select the ‘Decay Rates’ tab.
2. Select ‘Carbon-14’. Move the slider on the bucket to the right to add nuclei. Observe the decay of carbon-14 on the graph.
3. Click ‘Reset All’. Select ‘Uranium-238’. Move the slider on the bucket to the right to add nuclei. Observe the decay of uranium-238 on the graph.
4. Select the ‘Measurement’ tab.
5. Select the tree. Select the carbon-14 ‘Probe Type’. Click ‘Plant tree’ then click ‘Kill Tree’. Observe the changes that occur after the death of the tree. Repeat using the uranium-238 ‘Probe Type’.

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6. Repeat Step 5 for the rock, clicking ‘Erupt Volcano’ then ‘Cool Rock’.
7. Select the ‘Dating Game’ tab.
8. Drag the probe to an object. Choose the carbon-14 or the uranium-238 ‘Probe Type’ and look at the percentage. Drag the ‘Half-Lives’ slider so the percentage of carbon-14 or the uranium-238 matches. Use the graph to estimate the age of the object.
9. For some of the objects, you may not be able to obtain useful measurements — why is this? Note that objects found in the same layer of rock are likely to have similar ages.

Binding energy and mass defect

E.3.2: Binding energy and mass defect E.3.3: Binding energy per nucleon E.3.4: Mass-energy equivalence E.3.5: The strong nuclear force

Learning outcomes

By the end of this section you should be able to:

- Describe the strong nuclear force, nuclear binding energy and mass defect.
- Outline how binding energy per nucleon varies with nucleon number.
- Explain mass-energy equivalence and use the equation:

$$E = mc^2$$

You have probably heard of the equation $E = mc^2$, formulated by Albert Einstein (**Figure 1**) in 1905, but what does it mean? How is it relevant to measurements of the mass of atomic nuclei?

Student
view

Figure 1. Physicist Albert Einstein in 1905, the year he proposed that $E = mc^2$.

Source: "Albert Einstein ETH-Bib Portr 05937 (https://commons.wikimedia.org/wiki/File:Albert_Einstein_ETH-Bib_Portr_05937.jpg)" by Lucien Chavan / ETH Zürich is in the public domain

The strong nuclear force

Nuclei are composed of positively charged protons and neutral neutrons. Positive charges repel, so why are all nuclei other than hydrogen (which has just one proton) not unstable? How is it possible for nuclei of other elements to exist?

This question led physicists to hypothesise that nucleons are attracted to each other through another type of force. Calculations and observations supported this idea, and the force was named the strong nuclear force. Protons and neutrons experience this force (but electrons do not).

Unlike the gravitational force and the electric force, the strong nuclear force has a very short range, only attracting nucleons at separations (distances between their centres) of about 0.8 fm to 3.0 fm, where 1 fm = 10^{-15} m.

The typical separation between neighbouring nucleons in a nucleus is around 1 fm, and at this distance, the strong nuclear force between two nucleons is about 25 000 N.

The strong nuclear force balances the electrostatic repulsions between protons in the nucleus, and this is what prevents the nucleus from flying apart.

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Binding energy

The nuclear binding energy of a nucleus indicates how tightly bound the nucleus is. Binding energy is the work required to break apart a nucleus into its separate nucleons. We can use the symbol B_E to represent it, and we typically use the megaelectronvolt (MeV) as its unit. Binding energy increases as the number of nucleons in the nucleus increases, because it requires more energy to separate more nucleons.

In reality, nuclei do not break apart into individual nucleons. They usually break up by ejecting a small cluster of nucleons (alpha decay) or by the decay of a single nucleon into other particles (beta decay). A more useful quantity to indicate the stability of a nucleus is the average binding energy per nucleon, which is the binding energy of the nucleus divided by its number of nucleons, A. This can be written in symbols as $\frac{B_E}{A}$.

Figure 2 shows how the average binding energy per nucleon varies with the number of nucleons in the nucleus for stable nuclides.

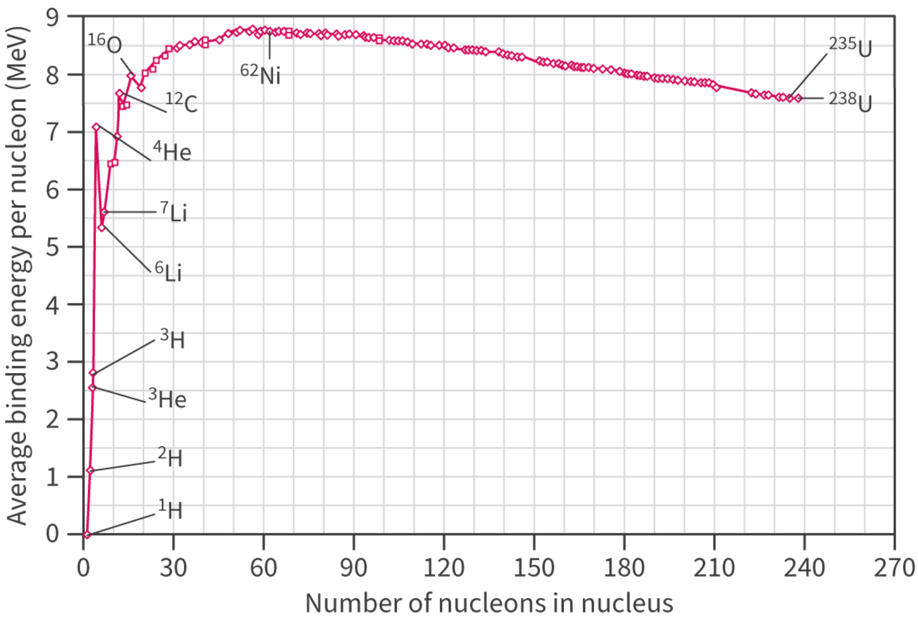

Figure 2. Graph of average binding energy per nucleon against number of nucleons in the nucleus.

More information for figure 2

The graph displays the average binding energy per nucleon in mega-electron volts (MeV) against the number of nucleons in a nucleus, ranging from 1 to 240 nucleons. The Y-axis represents average binding energy per nucleon in MeV, ranging from 0 to 9. The X-axis represents the number of nucleons, ranging from 0 to 270. Data points indicate that as the number of nucleons increases, the average binding energy per nucleon initially rises sharply to a peak and then gradually decreases or stabilizes with slight fluctuations. Specific elements like hydrogen (1), helium (4), carbon (12), nickel (62), lead (208), and uranium (235, 238) are labeled along the curve, indicating local maxima or specific points of interest in nuclear stability.

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Note the following points:

- Hydrogen-1 has no binding energy because it has only one nucleon. No work is required to break up the nucleus.
- Helium-4 does not fit the general pattern as it has a large average binding energy per nucleon. This means it is more stable than other nuclei with similar nucleon numbers.
- The average binding energy per nucleon initially increases as nucleon number increases, reaching its highest value, about 8.8 MeV, at nucleon numbers of around 60 (for nuclides of iron and nickel).
- To the right of the peak, the energy decreases with increasing nucleon number, but much less steeply.

Making connections

The average binding energy per nucleon is typically a few MeV. Compare this with the typical binding energy of an electron in a neutral atom (the work needed to remove the electron from the atom). This is the ionisation energy, and it is typically around 10 eV.

Roughly how many times greater are average binding energies per nucleon than electron ionisation energies? What does this tell us about how tightly bound electrons are in the atom compared with how tightly bound nucleons are in the nucleus?

Higher level (HL)

The gravitational potential energy of a system is the work done to assemble the system by bringing its components together from infinitely far apart (see subtopic D.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44096/)). How is this similar to binding energy? How is it different? Can you think of any reason why binding energy is often used by nuclear physicists instead of nuclear potential energy?

Look at this chart (https://www.thingsmadethinkable.com/item/nuclides.php) in which each dot represents a nuclide. If you are using a mouse or a touchpad, then hover over any green dot to see the specific data for that nuclide.

Unlike the graph in **Figure 2**, it shows most of the known unstable nuclides as well as the stable nuclides. Proton number increases to the right, so that each column of dots represents the isotopes of an element. Select ‘binding energy’. The key shows the binding energy per nucleon for each colour. Hover over a dot to see the nuclide and its binding energy per nucleon.

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Study skills

You do not have to recall the binding energy per nucleon for a particular nuclide, but you should know the general shape of the graph and the number of nucleons for which the energy is a maximum. In the region where the average binding energy per nucleon is decreasing, note that the **total** binding energy is still increasing.

Mass defect

Imagine that you have eight toy bricks, each with a mass of 2.0 g. You join all the bricks together to make a cuboid. When you measure the mass of the cuboid, it is 15.0 g. Of course, this is not actually possible. But it is what happens when nuclear masses are measured. The mass of a nucleus is less than the sum of the masses of the separate nucleons it is made from.

The difference between the mass of a nucleus and the sum of the masses of its separated nucleons is called the mass defect.

The mass of a nucleus and its nucleons can be measured in kilograms. However, a single proton has a mass of only 1.673×10^{-27} kg, so we use a much smaller unit of mass for nuclear calculations.

The (unified) atomic mass unit, u, is defined as one twelfth of the mass of a neutral carbon-12 atom:

$$1 \text{ u} = 1.661 \times 10^{-27} \text{ kg}$$

The rest masses (mass when they are isolated and not moving) of the proton, neutron and electron in u are:

proton: m_p = 1.007276 u
neutron: m_n = 1.008665 u
electron: m_e = 0.000549 u

(These are given in section 1.6.3 (/study/app/physics/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet.)

Study skills

In nuclear calculations, you will usually need to write masses and energies to at least six decimal places. If the proton and neutron rest masses were rounded to three significant figures, they would appear to be the same. These small differences are important in nuclear

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mass and energy calculations, which require a high degree of precision.

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Worked example 1

A carbon-12 nucleus has 6 protons and 6 neutrons.

Calculate the mass defect of the carbon-12 nucleus.

mass of carbon-12 atom = 12 u

m_p = 1.007276 u
m_n = 1.008665 u
m_e = 0.000549 u

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mass of carbon-12 nucleus (6 protons and 6 neutrons):

$$12 \text{ u} - (6 \times 0.000549 \text{ u}) = 11.996706 \text{ u}$$

total mass of 6 protons and 6 neutrons:

$$(6 \times 1.007276 \text{ u}) + (6 \times 1.008665 \text{ u}) = 12.095646 \text{ u}$$

$$\begin{aligned} \text{mass defect} &= 12.095646 \text{ u} - 11.996706 \text{ u} \\ &= 0.098940 \text{ u} \end{aligned}$$

To understand why atomic nuclei have a mass defect, it is necessary to find out more about the nature of mass and energy.

E = *mc* 2

Mass and energy were once considered to be two separate quantities. In 1905, Albert Einstein, building on work by scientists from the 1880s onwards, published a paper proposing that all mass is energy and all energy is mass.

This is known as mass-energy equivalence. Einstein’s equation is shown in **Table 1**.

Table 1. Einstein’s equation.

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Equation	Symbols	Units
$E = mc^2$	E = energy	joules (J)
	m = mass	kilograms (kg)
	c = speed of light in a vacuum, (3.00×10^8 m s^{-1})	metres per second (m s^{-1})

Einstein's equation does not mean that energy can change into mass and mass can change into energy. It expresses a more radical idea – mass and energy are the same thing.

Mass and energy are two separate quantities in the equation because we measure what appears to be mass in kilograms, and measure what appears to be energy in joules.

The constant c^2 is the conversion factor between the units. Note how different the kilogram and the joule are in scale – what we call 1 kg of mass is 9×10^{16} J of energy.

There are two reasons why it took us so long to realise that mass is energy.

- If an object gains energy (for example, by moving or being stretched), its mass increases. However, in most situations, the change is far too small to detect.
- Mass is the energy an object has because of the matter it is made of. It is 'hidden' energy. This energy can remain in the object for an indefinite amount of time without transferring to other forms of energy. Therefore, mass appears to be a separate quantity from other forms of energy.

Scientists sometimes refer to energy and mass using the term 'mass-energy'.

If a question asks for a mass to be 'converted into' energy, what it really means is: change the unit of some mass-energy from kilograms (or grams, or atomic mass units) into joules (or electronvolts).

Worked example 2

A paperclip has a mass of 1.0 g.

1. Convert the mass of the paperclip into joules.
2. If this could all be converted into electrical energy, calculate the length of time, in years, that a ten-watt flashlight could be run.

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Solution steps	Calculations
Step 1: Choose a suitable equation.	$E = mc^2$
Step 2: Convert the mass into kilograms.	$1.0\ \text{g} = 0.0010\ \text{kg}$
Step 3: Look up the speed of light in section 1.6.3 (/study/app/physics/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the IB physics data booklet.	$c = 3.00 \times 10^8$
Step 4: Substitute m and c into the formula to find E in joules.	$E = 0.0010 \times (3.00 \times 10^8)^2$ $= 9.0 \times 10^{13}\ \text{J}$ (or $90\,000\ \text{GJ}$)

2.

Solution steps	Calculations
Step 1: Use the equation relating power, work and time (where the work done is the energy supplied by the paperclip).	$P = \frac{\Delta W}{\Delta t}$
Step 2: Rearrange the equation and calculate the time.	$\Delta t = \frac{\Delta W}{P}$ $= \frac{9.0 \times 10^{13}}{10}$ $= 9.0 \times 10^{12}\ \text{s}$
Step 3: Convert by dividing by 60 (seconds in a minute), 60 (minutes in an hour), 24 (hours in a day), and 365 (days in a year).	$9.0 \times 10^{12} \div 60 \div 60 \div 24 \div 365 = 290\,000$ years (2 s.f.)

We can use other units with the equation $E = mc^2$:

- Energy, E, can be measured in MeV
- Mass, m, can be measured in $\frac{\text{MeV}}{c^2}$

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$1\frac{\text{MeV}}{c^2}$ is the amount of mass that would be written as 1 MeV in energy units (where $1 \text{ MeV} = 10^6 \text{ eV} = 10^6 \times 1.6 \times 10^{-19} \text{ J} = 1.6 \times 10^{-13} \text{ J}$).

Using $\frac{\text{MeV}}{c^2}$ for mass is convenient. It means that we do not need to use a calculation to convert between a unit used for mass and a unit used for energy. For example, a mass of $5.7 \frac{\text{MeV}}{c^2}$ is an energy of 5.7 MeV.

In these units, c is used as the unit of speed. That is, the speed of light is $1c$ where 1 is the value and c is the unit.

Study skills

A mass in $\frac{\text{MeV}}{c^2}$ is the mass we get if we divide the energy by the value of c^2.

Section 1.6.3 (/study/app/physics/sid-423-cid-762593/book/fundamental-constants-id-45155/)of the DP physics data booklet gives the mass of the proton, neutron and electron in kg, u and $\text{MeV}\,c^{-2}$. It also gives u in kg and $\text{MeV}\,c^{-2}$.

Worked example 3

Without referring to the DP physics data booklet, convert the atomic mass unit into:

1. joules
2. megaelectronvolts

Write your answers with the highest precision possible based on the values of the quantities given below.

$1 \text{ u} = 1.660539 \times 10^{-27} \text{ kg}$
$c = 2.997925 \times 10^{8} \text{ m s}^{-1}$
$e = 1.602176 \times 10^{-19} \text{ C}$

1.

Solution steps	Calculations
Step 1: Choose a suitable equation.	$E = mc^2$

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Solution steps	Calculations
Step 2: Substitute m and c into the formula to find E in joules.	$E = 1.660539 \times 10^{-27} \times (2.997925 \times 10^{8})^2$ $= 1.4924184 \times 10^{-10}$
Step 3: Write the answer to 7 significant figures because E and c are known to that level of precision.	$= 1.492418 \times 10^{-10}$ J (7 s.f.)

2.

Solution steps	Calculations
Step 1: Recall that 1 eV is the change in energy of an electron when it crosses a potential difference of one volt.	$1 \text{ eV} = 1.602176 \times 10^{-19}$ J
Step 2: Divide the energy from part 1 by the joule equivalent of an electronvolt (writing the energy from part 1 to at least 8 s.f. to avoid a rounding error).	$\frac{1.4924184 \times 10^{-10}}{1.602176 \times 10^{-19}} = 9.3149469 \times 10^{8}$ eV
Step 3: Round to 7 significant figures and convert to MeV.	$= 9.314947 \times 10^{2}$ MeV (7 s.f.) (or 931.4947 MeV)

In 1905, when Einstein published his paper, there was no experimental evidence that his equation $E = mc^2$ was an accurate model of the real world.

Higher level (HL)

Making connections

Einstein's argument that $E = mc^2$ was based on his special theory of relativity (see subtopic A.5 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-hl-id-45344/)).

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However, experiments in particle physics and nuclear physics have since shown that the measured masses of objects change when their kinetic energies change. We can observe these changes because when nuclei or subatomic particles undergo the large changes in speed that can be

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achieved experimentally, the effect on their mass is significant enough, and the mass measurements precise enough, that mass-energy equivalence is detectable. Mass defect is an example of observable evidence of mass-energy equivalence.

How is the mass defect of a nucleus related to its binding energy? Consider a nucleus B, with a large mass defect:

- The mass of the nucleus is much less than the mass of its separated nucleons.
- The energy of the nucleus is much less than the energy of its separated nucleons (since mass is energy).
- To separate the nucleus into its nucleons, the amount of energy in B would need to be supplied as work.
- The nucleus has a large binding energy (equal to the energy in B).
- The nucleus is difficult to separate into its individual nucleons. This difficulty in separating the nucleons is associated with stability.

Making connections

A nucleus that has a large binding energy per nucleon is relatively stable against fission or fusion (see subtopic E.4 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-46447/)). These two processes involve more extreme changes to the nucleus than radioactive decay.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Research skills — Evaluating information sources for accuracy, bias, credibility and relevance
- **Time required to complete activity**: 30 minutes
- **Activity type**: Individual activity

Using constants from section 1.6.3 (/study/app/physics/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP *Physics data booklet*, calculate:

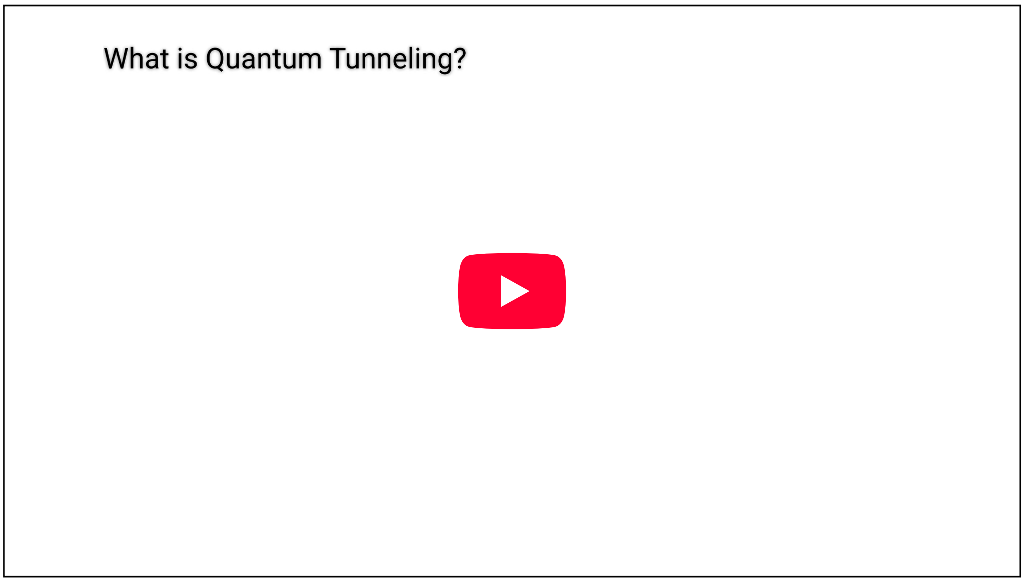
- the gravitational force between two neighbouring nucleons
- the electrostatic force between two protons.

(Assume that the particle separation — that is, the distance between the particles' centres — is 1×10^{-15} m.) Compare the forces you have calculated with the strong nuclear force between two neighbouring nucleons, which is around 20 000 N.

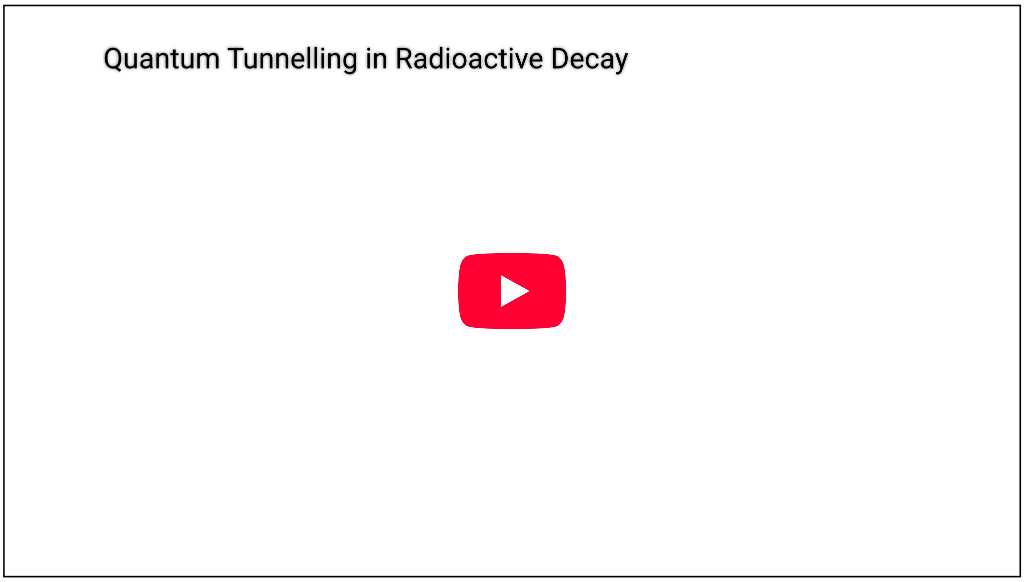
Student view

Extension

Research why all unstable nuclei do not decay immediately. The explanation comes from quantum physics. (Note that this is not required knowledge for the DP physics course, but you may find it interesting.) Explain this to one or more of your classmates. You could watch the following videos to help you:



Video 1. A brief introduction to 'quantum tunnelling'.



Video 2. An overview of tunnelling in alpha decay.

Or try the 'single atom' tab of the alpha decay simulation (https://phet.colorado.edu/sims/cheerpj/nuclear-physics/latest/nuclear-physics.html?simulation=alpha-decay).

5 section questions

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Question 1

SL HL Difficulty:

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The 1 protons ✓ in a nucleus are repelled by the 2 electrostatic ✓ force.

The protons and neutrons in a nucleus are attracted by the 3 strong nuclear ✓ force, which has a relatively short range.

Accepted answers and explanation

#1 protons

#2 electrostatic

#3 strong nuclear

General explanation

The protons in a nucleus are repelled by the electrostatic force.

The protons and neutrons in a nucleus are attracted by the strong nuclear force, which has a relatively short range.

Question 2

SL HL Difficulty:

The mass of a nucleus $^{A}_{Z}\mathrm{X}$ is M.

The mass of a proton is m_p and the mass of a neutron is m_n.

What is the correct expression for the mass defect of the nucleus?

1 $Zm_p + (A - Z)m_n - M$ ✓

2 $Am_p + (Z - A)m_n - M$

3 $M - Am_p - (Z - A)m_n$

4 $M - Zm_p - (A - Z)m_n$

Explanation

The mass of a nucleus is less than the mass of its separated nucleons (because its energy is less). The mass defect is the mass of the nucleus minus the mass of the separated nucleons.

The nucleus has A nucleons and Z protons, and $A - Z$ neutrons. The mass of the separate protons and neutrons is:

$$Zm_p + (A - Z)\, m_n$$

To find the mass defect, subtract the mass of the nucleus, M, from the above mass:

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$Zm_p + (A - Z)m_n - M$

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Question 3

SL HL Difficulty:

Nucleus X has a lower binding energy per nucleon than nucleus Y.

Which statement must be correct?

1. Nucleus X has a lower total binding energy than nucleus Y.
2. The mass defect of nucleus X is less than the mass defect of nucleus Y.

1 2 only ✓

2 neither of them

3 1 only

4 1 and 2

Explanation

The binding energy per nucleon depends on the total binding energy and the number of nucleons. If X has a larger number of nucleons than Y, then it is possible for X to have a lower binding energy per nucleon but a higher total binding energy.

The binding energy is the work needed to separate the nucleons of a nucleus. The energy needed to separate the nucleons of a nucleus can be measured in units of mass, and so the mass increases when the nucleons are separated.

Question 4

SL HL Difficulty:

Which statement is correct?

1. The mass of an object is a measure of the energy stored in it.
2. When a nucleus undergoes gamma decay, its mass decreases.
3. A nucleus of ${}^{1}_{1}\mathrm{H}$ has no mass defect.

1 1, 2 and 3 ✓

2 1 and 2

3 1 and 3

4 2 and 3

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Explanation

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Statement 1 expresses the concept of mass-energy equivalence. When the energy of an object increases, its mass increases because mass is a measure of energy.

When a nucleus undergoes gamma decay, the gamma ray carries energy away. The nucleus has less energy afterwards, and its mass is lower.

Statement 3 is true because this nucleus is a proton. No work is needed to break up this nucleus into separate nucleons.

Question 5

SL HL Difficulty:

The number of nucleons in a nucleus is A and the mass defect of the nucleus is $x\ \frac{MeV}{c^2}$.

The average binding energy per nucleon of this nucleus is $y\ MeV$.

x and y are unitless numbers

$c = 3.00 \times 10^8\ \mathrm{m\ s^{-1}}$

Which statement is correct?

1 $y = \frac{x}{A}$ ✓

2 $y = -\frac{x}{A}$

3 $y = \frac{\frac{x}{A}}{9.00} \times 10^{16}$

4 $y = \frac{x}{A} \times 9.00 \times 10^{16}$

Explanation

$x\ \frac{MeV}{c^2}$ is the equivalent mass we get if we divide $x\ MeV$ by c^2. The equivalent energy is $x\ MeV$.

Since $x\ \frac{MeV}{c^2}$ is the mass defect, $x\ MeV$ is the binding energy of the nucleus.

average binding energy per nucleon:

$$\frac{x}{A} MeV$$

E. Nuclear and quantum physics / E.3 Radioactive decay

Nuclear energies (HL)

Student view

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Explain that the radiation spectrums for alpha decay and gamma decay are evidence for discrete nuclear energy levels.
- Describe how the continuous spectrum of beta decay is evidence for the neutrino.

When a nucleus decays by emitting alpha particles or beta particles, a gamma ray is often emitted soon afterwards (typically after around 10^{-12} s). The gamma photons do not have a continuous range of possible energies. Instead, they have specific energies.

What explanation could there be for this observation? When have you encountered the emission of particles with a limited range of possible energies?

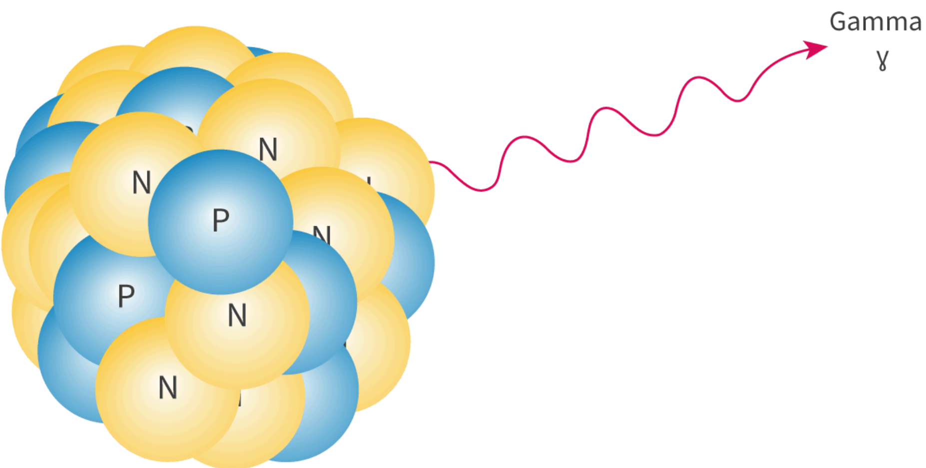

Figure 1. A nucleus emitting a gamma photon.

More information for figure 1

The diagram depicts a nucleus composed of protons and neutrons. The protons and neutrons are labeled with "P" and "N" respectively, and are arranged in a dense cluster, representing a typical atomic nucleus. A wavy arrow is shown moving away from the nucleus, labeled as "Gamma γ," indicating the emission of a gamma photon. This illustrates the process of gamma decay, where a nucleus in an excited state releases energy in the form of a gamma photon to move to a lower energy state. The arrow indicates the direction of the emitted gamma photon, symbolizing the energy transition.

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Energies in radioactive decay

Polonium-211 $\left({}^{211}_{84}\mathrm{Po}\right)$ is radioactive and decays into a stable isotope of lead, ${}^{207}_{82}\mathrm{Pb}$, by the emission of alpha particles and gamma rays.

The kinetic energies of the emitted alpha particles and the energies of the gamma photons have been measured. They have a small range of specific values:

- alpha particles: 5.9, 6.6, 6.9 and 7.5 MeV
- gamma photons: 0.3, 0.6, 0.9 and 1.0 MeV

Try to answer the following questions. Click on 'Show or hide solution' to see the sample answers.

1. Where have you encountered the emission of photons with discrete energies?

    Atomic spectra

    The emission spectrum of an element shows a series of bright lines at wavelengths/frequencies that are characteristic of that element.

2. What model do physicists use to explain the emission of photons with discrete energies?

    The model that places electrons within an atom into discrete (quantised) energy levels.

    Each possible photon energy is equal to a difference between two electron energy levels in the atom.

3. What model might explain the discrete energies of the gamma photons emitted by polonium-211?

    The model in which a nucleus has discrete energy levels.

    A nucleus can only emit photons with energies that equal the difference between pairs of energy levels.

4. Sketch an energy level diagram showing the energies involved in the decay of polonium-211 to lead-207.

    For hints on drawing your energy level diagram click on 'Show or hide tips'.

    Draw horizontal lines to represent the energy levels of the lead-207 nucleus, including its excited states and its ground state. Use arrows to show the energy changes that can be caused by gamma emission.

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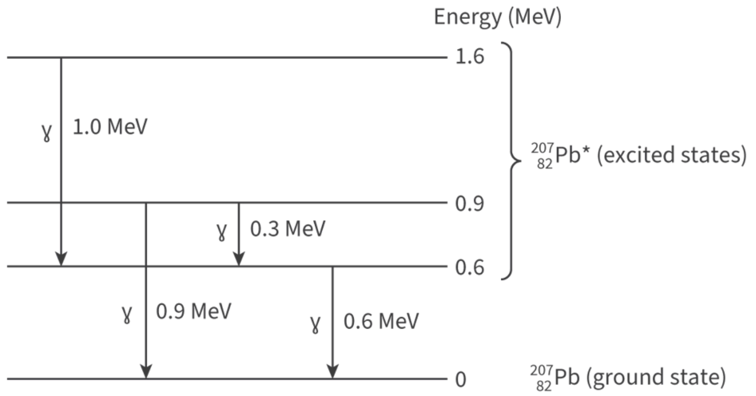
When Po-211 decays, it emits an alpha particle, or an alpha particle then a gamma photon. If a 7.5 MeV alpha particle is emitted, no gamma photon is emitted because the Pb-207 nucleus is in its lowest energy state.

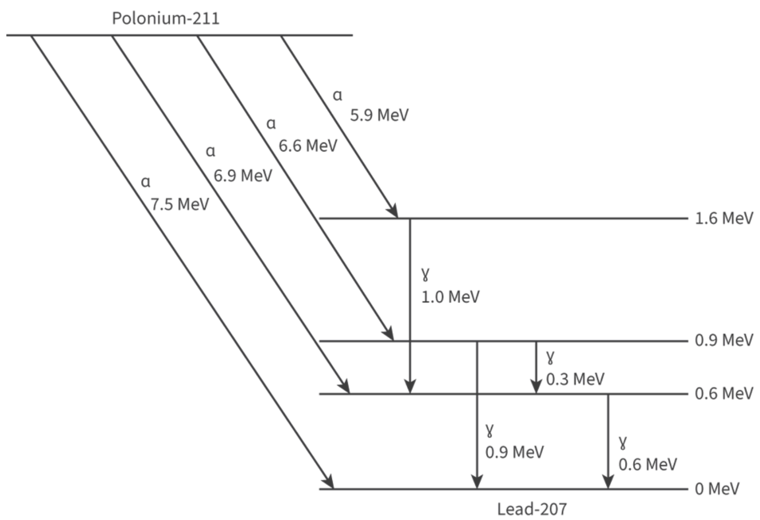
In an atom, transitions between all possible pairs of electron energy levels can occur. However, not all transitions between pairs of nuclear energy levels are possible in Pb-207.

Two of the possible alpha particle energies are 7.5 MeV and 6.9 MeV. The difference between them, 0.6 MeV, equals one of the gamma photon energies.

The first energy level diagram shows the energy levels that can be deduced for the lead-207 nucleus. Each energy level is shown as a horizontal line. Energy transitions resulting from the emission of gamma, γ, photons are shown as arrows labelled with their energies.



This more detailed diagram also shows the alpha (α) particle energies (not to scale). Are the four Pb-207 nuclear energy levels consistent with the observed alpha and gamma energies?



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Observations that alpha particles and gamma photons from radioactive decays always have discrete energies led to a model in which the energy of a nucleus is quantised.

In addition to a lowest energy state or ground state, each nuclide has a particular set of possible excited states. This has parallels with the model of quantised electron energies in atoms (see subtopic E.1 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43191/)).

After an alpha decay, the nucleus may be in an excited state. In this case, the nucleus will lose energy by emitting one or more gamma photons until it reaches its ground state. However, if emitting an alpha particle leaves the nucleus in its ground state, there will be no subsequent emission of gamma photons. This explains why most alpha sources are also sources of gamma rays.

Figure 2 shows an energy level diagram for the radioactive decay of radium-226 into radon-222.

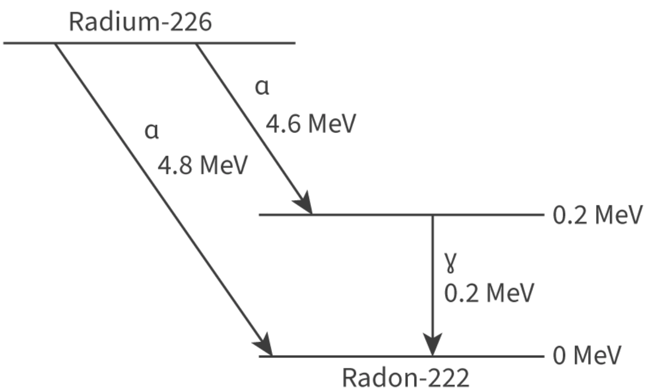

Figure 2. An energy level diagram for the decay of radium-226 into radon-222.

More information for figure 2

This is an energy level diagram showing the decay process of radium-226 into radon-222. The diagram starts with a horizontal line labeled 'Radium-226' at the top. Two diagonal arrows lead downward from this line, each indicating a different alpha particle emission with energy values: one labeled 'α, 4.8 MeV' and the other 'α, 4.6 MeV'. The arrow labeled 'α, 4.8 MeV' leads directly to a level labeled 'Radon-222', indicating that no gamma photon is emitted. The arrow labeled 'α, 4.6 MeV' leads to an intermediate level 0.2 MeV above the final 'Radon-222' state. From this intermediate level, a vertical arrow labeled 'γ, 0.2 MeV' indicates the emission of a gamma photon as it drops to the 'Radon-222, 0 MeV' level.

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If the radium-226 nucleus emits a 4.8 MeV alpha particle, the radon-222 nucleus is not excited and does not emit a gamma photon. However, if the radium-226 nucleus emits a 4.6 MeV alpha particle, the radon-222 nucleus is in an excited state and emits a 0.2 MeV gamma photon.

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The discovery of the neutrino

When a nucleus undergoes alpha decay, the energies of the alpha particles and any emitted gamma photons are discrete. However, in beta decay, the energies of the beta particles are continuous – they can take any value within a particular range.

Figure 3 shows the energy spectrum of beta particles emitted during beta-minus decay. There is a maximum energy, E_{max}.

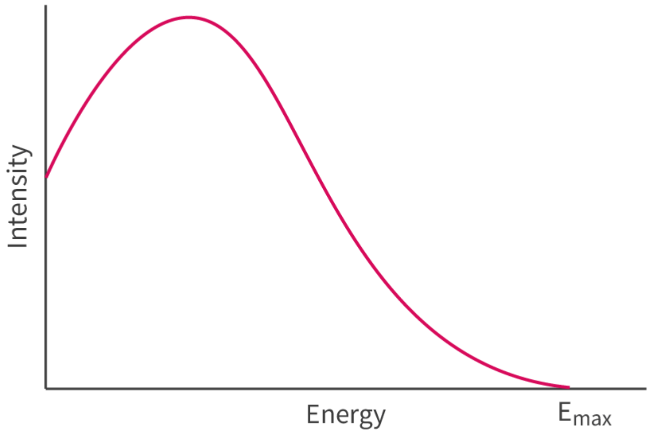

Figure 3. The typical shape of the beta particle energy spectrum in beta-minus decay.

More information for figure 3

The image is a graph representing the energy spectrum of beta particles emitted during beta-minus decay. The horizontal axis is labeled 'Energy' and has an endpoint labelled 'Emax,' indicating the maximum energy. The vertical axis is labeled 'Intensity.' The graph features a single curve that rises, reaches a peak, and then tapers off, forming a bell-like shape. The curve starts at the origin, increases to a maximum point, and then gradually declines towards the maximum energy, Emax.

[Generated by AI]

This graph does not fit the model of discrete energy levels within the nucleus, in which emitted particles have a limited number of energies. Niels Bohr, the physicist who developed the model of electron energy levels within an atom, suggested that radioactive decay could break the law of conservation of energy.

In 1930, the physicist Wolfgang Pauli proposed that another (as yet undetected) particle was emitted during beta decay. The beta particle and the other particle share the available energy in varying proportions.

This hypothesis was increasingly supported by evidence and came to be accepted. The other particle in beta-minus decay is now known as an antineutrino (or a neutrino in beta-plus decay).

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Figure 4 shows a typical antineutrino energy spectrum for beta-minus decay. Compare it with **Figure 3** – what do you notice?

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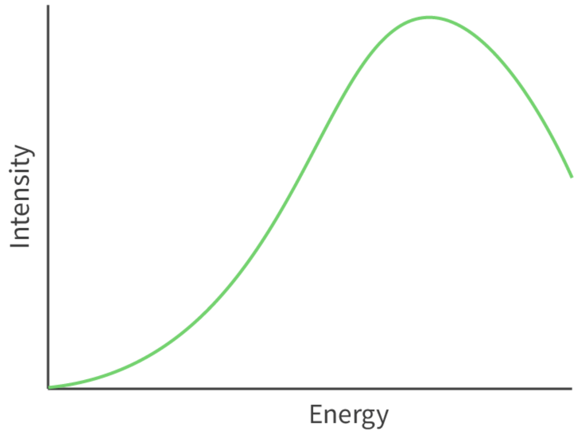

Figure 4. The typical shape of the neutrino (or antineutrino) particle energy spectrum in beta decay.

More information for figure 4

The image is a graph illustrating the typical antineutrino energy spectrum in beta-minus decay. The X-axis represents Energy, while the Y-axis represents Intensity. The graph displays a curved line that starts at the origin, rises to a peak at a mid-range energy level, and then gradually declines. This shape indicates that there is a specific energy level where the intensity of the antineutrino is at its highest, followed by a decrease in intensity as the energy level exceeds that point.

[Generated by AI]

Making connections

An antineutrino is emitted in beta-minus decay and a neutrino is emitted in beta-plus decay (see section E.3 (/study/app/physics/sid-423-cid-762593/book/nuclear-radiation-id-46543/)). Although the existence of these particles was proposed in 1930, they were not detected until 1956. Neutrinos and antineutrinos have extremely low mass and interact very weakly with other matter. **Video 1** shows some information about neutrinos.

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Video 1. Why neutrinos matter.

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In a beta-minus decay the antineutrino takes more of the energy than the beta particle – can you explain why?

Assume that the kinetic energy released in the decay is all shared between the beta particle and the antineutrino. Consider conservation of momentum.

If the masses of the beta particle and the antineutrino are m_β and m_ν and the velocities after the decay are v_β and v_ν, then for momentum to be conserved:

$$m_\beta v_\beta = -m_\nu v_\nu$$

The velocity of the antineutrino can be written as:

$$v_\nu = -\frac{m_\beta}{m_\nu} v_\beta$$

m_β is much greater than m_ν, so v_ν is much greater than v_β.

The kinetic energy of the beta particle is

$$E_\beta = \frac{1}{2} m_\beta v_\beta^2$$

and the kinetic energy of the antineutrino is $E_\beta = \frac{1}{2} m_\nu v_\nu^2$ which can be rewritten as:

$$E_\nu = \frac{1}{2} m_\nu \left(\frac{m_\beta}{m_\nu} v_\beta \right)^2 = \frac{1}{2} \frac{m_\beta}{m_\nu} m_\beta v_\beta^2 = E_\beta \times \frac{m_\beta}{m_\nu}$$

Since $m_\beta > m_\nu$, the kinetic energy of the antineutrino is greater than the kinetic energy of the beta particle.

A similar argument can be applied to beta-plus decay.

Worked example 1

Cobalt-60 $\left({}^{60}_{27}\text{Co}\right)$ is an artificially created nuclide that is used for the sterilisation of medical equipment, where high-energy gamma rays are used to destroy microorganisms on the surface of the equipment.

${}^{60}_{27}\text{Co}$ decays to nickel-60 by emitting beta-minus particles and gamma photons.

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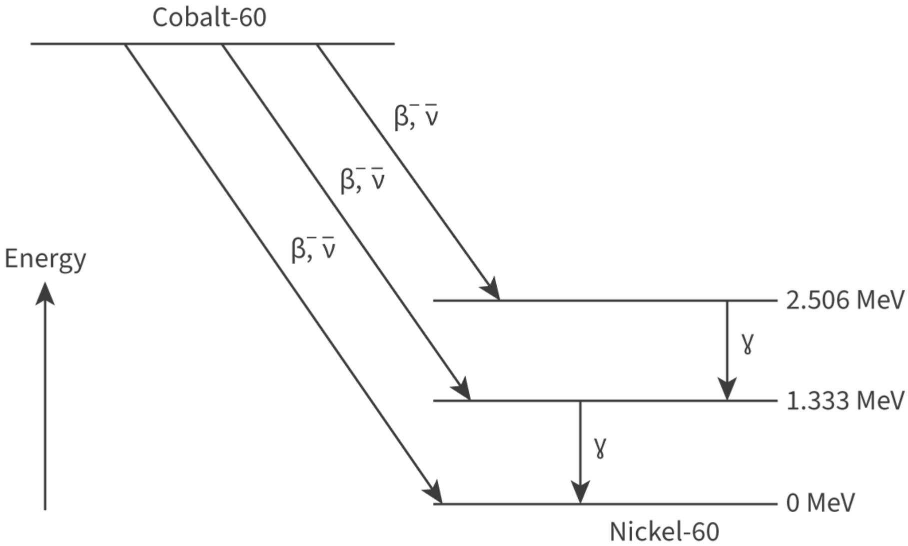

Figure 5. Beta decay of cobalt-60 into nickel-60.

More information for figure 5

The diagram illustrates the process of beta decay of cobalt-60 into nickel-60. On the left side, cobalt-60 is shown at a higher energy level. Arrows marked with 'β^−, ν̄' indicate the emission of beta particles and antineutrinos as the energy level decreases. The initial transition shows cobalt-60 releasing energy to reach a stable state as nickel-60 at the lower energy level.

The energy scale is depicted vertically on the left with a labeled transition at '2.506 MeV', representing the energy level after the first gamma emission. Another arrow at '1.333 MeV' shows a further drop in energy. The base level is labeled '0 MeV', indicating the final energy state of nickel-60. This energy descent process includes gamma decay represented by 'γ' symbols aligning with the arrows pointing downward.

Each segment of the diagram corresponds to a specific energy level transition, showing the sequential emission of particles and energy.

[Generated by AI]

What are the possible energies for the gamma photons emitted in this process?

According to the diagram, there are two possible gamma photon energies:

- the energy difference between the first excited state (1.333 MeV) and the ground state (0 MeV)
- the energy difference between the second excited state (2.506 MeV) and the first excited state (1.333 MeV)

The two possible energies are:

- 1.333 MeV
- 2.506 — 1.333 = 1.173 MeV

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Making connections

Linking question: How did conservation lead to experimental evidence of the neutrino?

Work through the activity to check your understanding of nuclear energies.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Answer the following questions about nuclear energies.

1. Explain why the alpha particles emitted from a nuclide have discrete energies, while the beta particles emitted from a nuclide have a continuous range of energies.
2. The caesium-137 isotope $\left({}^{137}_{55}\mathrm{Cs}\right)$ decays by beta-minus decay into an excited state of barium-137, which decays by emitting a gamma photon. The half-life for the decay of the excited state into the ground state is about 2.5 minutes (rather than a fraction of a second, as is typical). A relatively long-lived excited state is known as a 'metastable' state. The metastable state of barium-137 is barium-137m $\left({}^{137\mathrm{m}}_{56}\mathrm{Ba}\right)$.

   Sketch an energy level diagram using the following information. Label the particle type and the energy for each possible energy transition.

   • Caesium-137 can also decay by beta-minus decay directly into barium-137 in the ground state.
   • The minimum value for the combined energy of the beta-min particle and the antineutrino is 0.514 MeV.
   • The energy of the gamma photon is 0.662 MeV.

3. The isotope molybdenum-99 decays by beta emission into a metastable technetium isotope, technetium-99m. The half-life of technetium-99m is 6 hours. Technetium-99 is a beta emitter with a half-life of over 200 000 years. Any technetium that enters the human body is excreted within 24 hours. Suggest why technetium-99m is useful in medicine.
4. An isotope of radon, ${}^{211}_{86}\mathrm{Rn}$, decays into polonium (Po). The graph shows an energy diagram for this decay.

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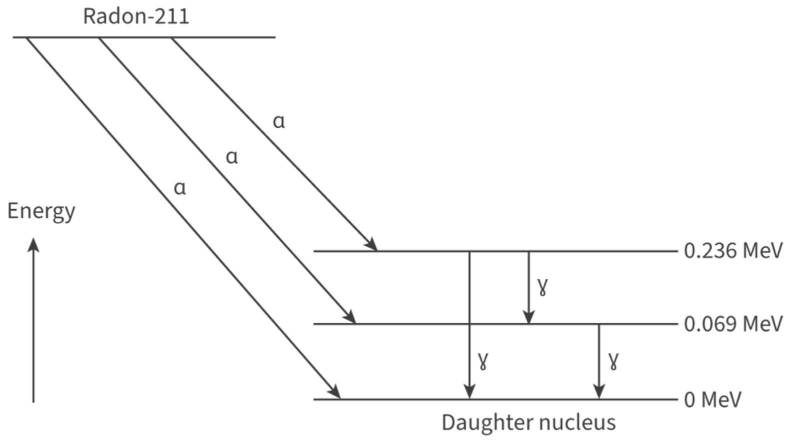

Figure 6. An energy diagram to show radon decaying into polonium.

More information for figure 6

The diagram illustrates the decay process of radon into polonium through a series of energy transitions. The initial stage at the top is marked as Radon-211. The decay process involves alpha (α) and gamma (γ) emissions. The diagram explicitly labels each transition. As radon decays, it loses energy, moving through three distinct pathways each labeled as 'α'.

The energy transitions move downward at angles, directed towards the center of the diagram, converging into a series of horizontal lines which represent different energy levels. Two values are labeled at the right side of these horizontal lines: 0.236 MeV and 0.069 MeV, and ultimately reaching the base energy level marked as 0 MeV.

The term 'Daughter nucleus' is labeled at the bottom, indicating the final state after the decay process. The left side of the diagram is labeled 'Energy', with an upward arrow denoting the increase in energy levels vertically.

[Generated by AI]

1.

Energy level diagram for the decay of radon-211 (not to scale).

(a) Write a decay equation for the decay of a radon-211 nucleus into an excited nucleus of polonium.
(b) Write a decay equation for the decay of an excited nucleus of polonium into the ground state.
(c) Determine the three possible energies of the gamma photons emitted when after the alpha decay the excited nuclei decay into the ground state.
(d) Determine the wavelength of the highest energy gamma photon emitted.

$(c = 3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}\ \text{and}\ h = 6.63 \times 10^{-34}\ \mathrm{J\ s})$

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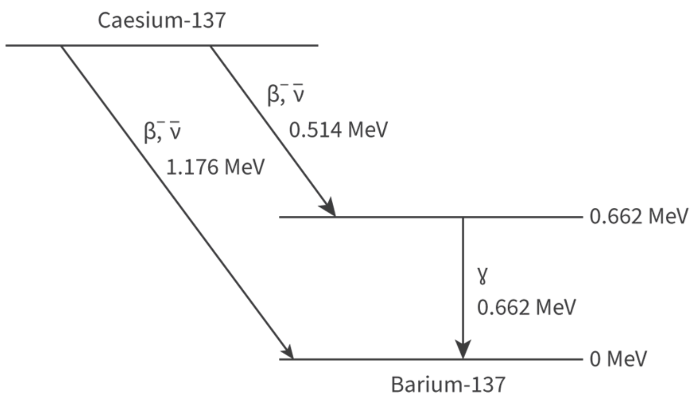
1. Atomic nuclei have discrete energies. A nuclide has a particular set of energy levels, with the lowest called the ground state.

   An alpha decay may occur in isolation, or it may be followed by one or more gamma decays. Each decay decreases the energy of the nucleus, and the end result is that the nucleus is in its ground state. The only possible energy changes of the nucleus are those that equal the difference between two of its energy levels. In each decay, an alpha particle or a gamma photon carries away energy equal to one of these differences. Hence, the emitted alpha particles and gamma photons have discrete energies.

   In each beta decay, the nucleus expels energy equal to the difference between two of its energy levels. However, a beta particle is always emitted with a neutrino (a beta-minus particle with an antineutrino and a beta-plus particle with a neutrino). The two particles share the energy lost by the nucleus. The energies of free particles are not discrete, so the beta particle and the neutrino share the energy in varying proportions. The emitted beta particles (as well as the neutrinos) have continuous energies.

2. 

   Energy level diagram for the beta decay of caesium-137 (not to scale).

3. Gamma emitters are used as tracers in nuclear medicine. The gamma source is swallowed or injected, and a gamma camera creates an image from the gamma radiation that emerges from the body. Alpha particles and beta particles are more ionising than gamma rays, and could cause considerable damage to the body. Therefore a gamma emitter is needed.

   There is no known pure gamma emitter, but if a pure sample of technetium-99m can be obtained then it can be used as a tracer. The half-life of 6 hours is long enough for a procedure to be carried out.

   Technetium-99m decays into technetium-99, which is radioactive. However, the half-life of over 200 000 years is so long that if the amount of tracer used is relatively small, the activity will be very low. It will not cause harmful levels of ionisation to the body in the 24 hours

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it takes for the tracer to be excreted.

4. (a) ${}^{211}_{86}\mathrm{Rn} \rightarrow {}^{207}_{84}\mathrm{Po}^{*} + {}^{4}_{2}\alpha$

(b) ${}^{207}_{84}\mathrm{Po}^{*} \rightarrow {}^{207}_{84}\mathrm{Po} + \gamma$

(c) $0.069\ \mathrm{MeV},\ 0.167\ \mathrm{MeV},\ 0.236\ \mathrm{MeV}$

(d) $\text{highest energy} = 0.236\ \mathrm{MeV} = 3.776 \times 10^{-14}\ \mathrm{J}$

for a photon, $E = hf$
but for a wave, $c = f\lambda$

$$\begin{aligned}\lambda &= \frac{c}{f}\\ &= \frac{hc}{E}\\ &= \frac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{3.776 \times 10^{-14}}\\ &= 5.27 \times 10^{-12}\ \mathrm{m}\ (3\ \mathrm{s.f.})\end{aligned}$$

5 section questions ^

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Question 1

HL Difficulty:

In the decay of a radioactive nuclide, the energies of 1 alpha ✓ particles and gamma photons can only take a finite number of specific values. This is because the energies of a 2 nucleus ✓, like the energies of electrons in atoms, are 3 discrete ✓ .

Accepted answers and explanation

#1 alpha

#2 nucleus

#3 discrete
quantized
quantised

General explanation

In the decay of a radioactive nuclide, the energies of alpha particles and gamma photons can only take a finite number of specific values. This is because the energies of a nucleus, like the energies of electrons in atoms, are discrete.

Question 2

HL Difficulty:

Which of the following laws was used to deduce that antineutrinos (and neutrinos) exist?

1 Conservation of energy ✓

2 Conservation of charge

3 Conservation of momentum

4 Conservation of particle number

Explanation

The existence of the antineutrino was proposed because the electrons in beta decay were observed to have a continuous spectrum of energies.

Given the evidence from alpha and gamma decay that nuclear energies are discrete, beta particle energies were also expected to be discrete. The fact that they are continuous led to the idea that the energy in beta decay is shared between the beta particle and another particle (in varying proportions). This particle came to be known as the neutrino.

Student view

Question 3

HL Difficulty:

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A parent nucleus decays by emitting an alpha particle. Sometimes, the alpha decay is followed by a gamma decay but sometimes it is not. When gamma decay occurs, there are three possible energies of the gamma photon.

What is the smallest possible number of excited states of the daughter nucleus?

1 2 ✓

2 3

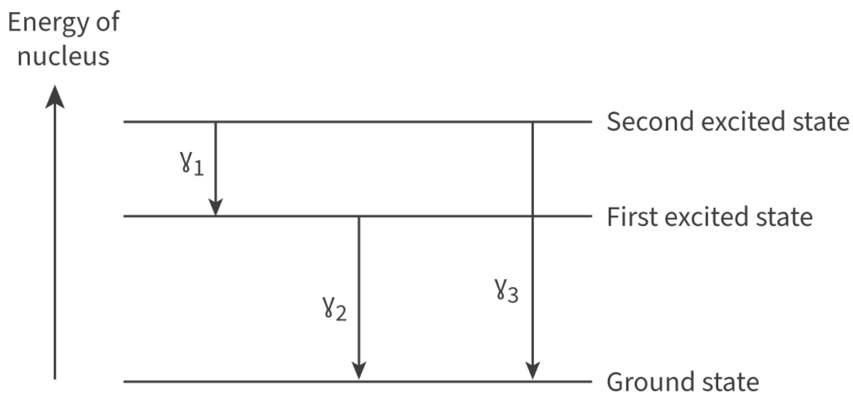
3 4

4 5e

Explanation

The energy of an emitted gamma photon equals an energy difference between two energy states of the daughter nucleus.

If there are three possible gamma photon energies, then the smallest possible number of excited states is 2. The diagram shows a nuclear level diagram for the nucleus, with the three different gamma transitions as γ_1, γ_2 and γ_3.



More information

Question 4

HL Difficulty:

A nucleus $^{A}_{Z}\mathrm{X}$ decays by beta-minus decay. The daughter nucleus has two possible excited states.

Which of the following explains why beta-minus particles from the decay of $^{A}_{Z}\mathrm{X}$ have a continuous spectrum of energies?

1 Energy is shared in varying proportions between the beta-minus particle and an antineutrino. ✓

2 Energy is shared in varying proportions between the beta-minus particle and a photon.

3 There are up to three possible energy states of the daughter nucleus after the beta-minus decay.

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4 There are one or two possible energy states of the daughter nucleus after the beta-minus decay.

Explanation

In beta-minus decay, the parent nucleus changes into a daughter nucleus of lower energy. The energy difference is carried away by the beta-minus particle and an antineutrino. These two particles share the energy in varying proportions, which is why the beta-minus particles have a continuous spectrum of energies.

The total energy change in the decay from the parent nuclide to a stable daughter is shared between a beta-minus particle and an antineutrino, and 0, 1 or 2 gamma photons. However, gamma photons have discrete energies, corresponding to energy differences between the daughter nuclide's quantised energy levels. This does not explain the continuous spectrum of the beta-minus particle energies.

Since the daughter nucleus has two excited states, there are up to three possible energy states of the daughter nuclide (ground, first excited or second excited state) after the beta-minus decay. (Fewer than three of these may actually occur; it depends on which energy transitions are possible in the beta-minus decay.) This does not explain the continuous spectrum of the beta-minus particle energies.

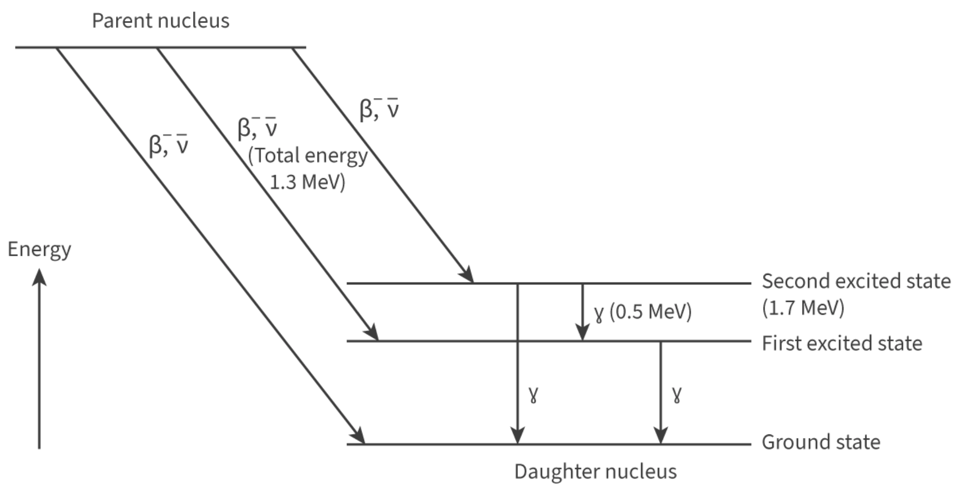
Question 5

HL Difficulty:

Determine the maximum possible energy for a beta-minus particle from the decays shown in the diagram.

Assume the energy of the antineutrino to be negligible.

Give your answer to an appropriate number of significant figures.



More information

The energy is 1 2.5 MeV

Student view

Accepted answers and explanation

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#1 2.5

General explanation

The diagram shows that after the beta-minus decay, the daughter nucleus may be in one of two excited states, or in the ground state. If the daughter nucleus is excited, then it emits one or more gamma photons to reach the ground state.

The highest-energy transition involving a beta-minus particle is the transition from the parent nucleus to the daughter nucleus in its ground state (with energy 0 MeV). The energy of this transition can be deduced from energies given in the diagram: it is the sum of 1.3 MeV and 1.7 — 0.5 = 1.2 MeV. The energy is 2.5 MeV.

The beta-minus particle and antineutrino share this energy. However, since the question states that the energy of the antineutrino is negligible, the energy of the beta-minus particle can be taken as 2.5 MeV.

E. Nuclear and quantum physics / E.3 Radioactive decay

Radioactive decay law (HL)

E.3.19: The radioactive decay law and the decay constant (HL) E.3.20: Probability of decay and the decay constant (HL)
E.3.21: Activity as the rate of decay (HL) E.3.22: Relationship between half-life and the decay constant (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Outline the decay constant and know that it only approximates the probability of decay in a unit of time.
- Explain the radioactive decay law and use the equation:

$$N = N_0 e^{-\lambda t}$$

- Describe activity as the rate of decay and use the equation:

$$A = \lambda N = \lambda N_0 e^{-\lambda t}$$

- Describe the relationship between the decay constant and half-life and use the equation:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

Student view

Radioactive waste from nuclear power stations contains a variety of radioactive nuclides (**Figure 1**). We need to predict the future activity of this waste so that we can decide how to store it safely.

Figure 1. Radioactive waste.

One of the radioactive isotopes in nuclear waste is plutonium-239, which has a half-life of 24 000 years. If we know the activity of a container of plutonium-239 today, we can use half-life to predict its activity at 24 000-year intervals. How can we predict the activity at other times?

Decay constant and radioactive decay law

For a pure sample of a radioactive nuclide, the activity, A, (number of decays per second) is proportional to the number of undecayed nuclei that remain:

$$A \propto N$$

For example, if the number of undecayed nuclei, N, falls by half, the activity falls by half.

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The constant of proportionality in this relationship is called the decay constant, (/study/app/physics/sid-423-cid-762593/book/activity-solar-system-id-46567/) λ. The equation for activity is shown in **Table 1**.

Table 1. Equation for activity.

Equation	Symbols	Units
$A = \lambda N$	A = activity	Bq (decays per second, s^{-1}) (or other reciprocal unit of time)
	λ = decay constant of nuclide	per second, s^{-1} (or other reciprocal unit of time)
	N = number of undecayed nuclei	unitless

The unit of the decay constant is a reciprocal of a unit of time, such as s^{-1} or minute^{-1}. In the equation above, λ and A have the same unit because N is unitless.

The value of the decay constant differs for different nuclides. The decay constant is a measure of how quickly a radioactive nuclide decays. A larger decay constant is associated with a shorter half-life and a higher activity for any given number of atoms in a sample.

Study skills

λ is also used as the symbol for wavelength, but it should be clear from the context which quantity the symbol represents. Can you think of any other symbols that are used to represent two different quantities or units in physics?

If a number of the nuclei, ΔN, in a sample decay during time interval Δt, then the average rate of change of undecayed nuclei in that time interval is $\frac{\Delta N}{\Delta t}$. This has a negative value because N is decreasing.

The average activity during the time interval equals the magnitude of $\frac{\Delta N}{\Delta t}$, since activity is a positive quantity. $\frac{\Delta N}{\Delta t}$ is an approximation to the actual activity at any point during the time interval. Therefore, using the relationship $A = \lambda N$:

$$\frac{\Delta N}{\Delta t} \approx -\lambda N$$

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The smaller the time interval Δt, the more closely $\frac{\Delta N}{\Delta t}$ approximates $-\lambda N$. From this relationship, it is possible to derive (using calculus), the equation shown in **Table 2**.

Table 2. The equation for the number of undecayed nuclei remaining.

Equation	Symbols	Units
$N = N_0 e^{-\lambda t}$	N = number of undecayed nuclei remaining	unitless
	N_0 = initial number of undecayed nuclei	unitless
	λ = decay constant of nuclide	per second, s^{-1} (or other reciprocal unit of time)
	t = time (t = 0 at the start, when N = N_0)	seconds, s (or other unit of time)

This is known as the radioactive decay law. The unit of λ is the reciprocal of the unit of t.

Worked example 1

A sample of 3.0×10^9 radioactive nuclei decay into a stable element in a single decay.

The decay constant of the sample is $5.6 \times 10^{-3}\ s^{-1}$.

How many radioactive nuclei remain after 20 minutes?

Using the equation above:

$$N = N_0 e^{-\lambda t}$$

Substituting the given values:

$$N = 3 \times 10^9 e^{-0.0056 \times 20 \times 60}$$

$$N = 3.6 \times 10^6$$

Study skills

You will not need to recall the value of e. Scientific calculators have a built-in exponential function, often shown by a label e^x.

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Note that in any given scenario involving a radioactive nuclide sample, there are only two variables in the decay law equation:

N and *t*

Aspect: Models

$N = N_0 e^{-\lambda t}$ is an example of an exponential function. Exponential functions can be used to model real-life scenarios in which the rate of change of a quantity is proportional to the value of the quantity, such as the growth of a population.

Which areas of physics involve exponential change?

If the decay constant of the nuclide and the initial number of nuclei are known, the equation $N = N_0 e^{-\lambda t}$ can be used to predict the number of nuclei remaining in a sample at any time in the future.

Since $A = \lambda N$, the relationship between activity and time is given by the equation in **Table 3**.

Table 3. The equation for activity.

Equation	Symbols	Units
$A = \lambda N_0 e^{-\lambda t}$	A = activity	per second, s^{-1} (or other reciprocal unit of time)
	λ = decay constant of nuclide	per second, s^{-1} (or other reciprocal unit of time)
	N_0 = initial number of undecayed nuclei	unitless
	t is the time (where t = 0 at the start, when $N = N_0$)	seconds, s (or other unit of time)

This equation can also be written as:

$$A = A_0 e^{-\lambda t}$$

where $A_0 = \lambda N_0$ is the initial activity of the sample.

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Worked example 2

The radionuclide fluorine-18 is used in nuclear medicine. Its decay constant is 0.379 hour^{-1}.

The activity of a pure sample of fluorine-18 is 1.71×10^{21} hour^{-1}. It decays into a stable nuclide.

Predict the activity of the sample after 150 minutes.

Solution steps	Calculations
Step 1: Write the relationship between activity and time.	$A = \lambda N$ where: $N = N_0 e^{-\lambda t}$ so: $A = \lambda N_0 e^{-\lambda t}$ (where λN_0 is the initial a
Step 2: The decay constant and time should have reciprocal units of each other when used in the decay equation, so convert time into hours (or decay constant into minutes^{-1}).	$t = 150$ mins $= 2.50$ hours
Step 3: Substitute the values of initial activity, λ and t (where t is the time since the activity had its initial value).	$A = 1.71 \times 10^{21} \times e^{-0.3}$ $= 6.63 \times 10^{20}$ hour^{-1}

The background-corrected count rate C of a sample, measured using a consistent method, is proportional to the activity A.

If the initial count rate is C_0, the relationship between count rate and time is:

$$C = C_0 \mathrm{e}^{-\lambda t}$$

The radioactive decay law can be written in the three ways shown in **Table 4.**

Table 4. The radioactive decay constant.

Student view

Number of undecayed nuclei, *N*	Activity, *A*	Count rate, *C*
$N = N_0 e^{-\lambda t}$	$A = \lambda N_0 e^{-\lambda t}$ $A = A_0 e^{-\lambda t}$	$C = C_0 e^{-\lambda t}$

Graphs of N, A or C against time have the characteristic shape of an exponential decay relationship shown in **Figure 2**.

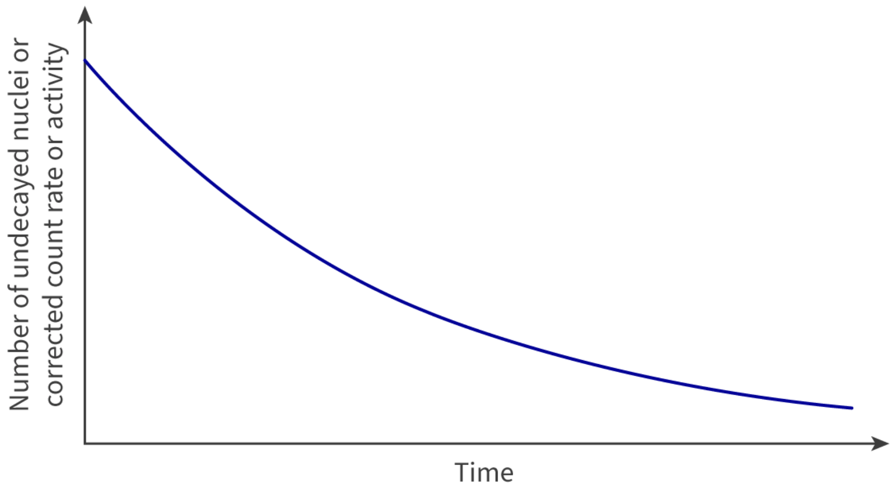

Figure 2. The exponential nature of radioactive decay.

More information for figure 2

This is a graph illustrating exponential decay. The X-axis represents time, while the Y-axis represents the number of undecayed nuclei or corrected count rate or activity. As time increases, the value on the Y-axis decreases, forming a downward-sloping curve. This curve demonstrates the characteristic shape of an exponential decay, typically found in radioactive decay processes. The gradient at any point on the curve represents the decay rate, aligning with the negative exponential equations (-λN, -λA, -λC) described for different variables in the context of the images before and after description.

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In the case of an N–t graph, the gradient at any given time equals $-\lambda N$ at that instant. Similarly, the gradient of an A–t graph equals $-\lambda A$ and the gradient of a C–t graph equals $-\lambda C$.

Worked example 3

A Geiger counter is set up to measure the count rate from a pure sample of a nuclide over a period of time. The nuclide has a decay constant of 0.0013 s^{-1}.

The initial count rate is 8400 counts s^{-1}.

After what period of time is the count rate 5500 counts s^{-1}?

(Assume that the background count is negligible compared with the source count rate.)

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Solution steps	Calculations
Step 1: Write the known quantities.	$\lambda = 0.0013\ \text{s}^{-1}$ $C_0 = 8400\ \text{cou}$ $C = 5500\ \text{coun}$
Step 2: Write the relationship between source count rate and time.	$C = C_0 e^{-\lambda t}$
Step 3: Rearrange the equation to make t the subject: start by dividing both sides by C_0.	$\frac{C}{C_0} = e^{-\lambda t}$
Step 4: Take the natural logarithm of both sides.	$\ln \frac{C}{C_0} = -\lambda t$
Step 5: Divide both sides by $-\lambda$ and then substitute the known values of λ, C_0 and C.	$t = \frac{\ln \frac{C}{C_0}}{-\lambda}$ $= \frac{\ln \frac{5500}{8400}}{-0.0013}$ $= 325.76\ \text{s}$ $= 330\ \text{s (2 s.f.}$

Using logarithmic graphs to show decay relationships

The half-life of a radioactive nuclide can be deduced from a graph of count rate against time (see section E.3.3a (/study/app/physics/sid-423-cid-762593/book/half-life-id-46544/)). However, there are two disadvantages to this method when working with real data.

- To estimate the half-life, a best fit curve must be drawn. While a best fit exponential decay curve can be drawn using technology, drawing the curve by hand may be difficult, especially if there is significant scatter in the data.
- If the measurements of a source are taken over a time period that is less than the half-life, the half-life cannot be easily read from an exponential decay curve (although it is possible to deduce it from a measured gradient).

The relationship between background-corrected count rate and time can be expressed in a different way that enables a linear graph to be drawn. This resolves the problems above.

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Practical skills

Tool 3: Mathematics — Graphing
Inquiry 2: Collecting and processing data — Interpreting results

When the relationship between two measured variables is non-linear, it can be difficult to extract information from the curved graph or to see whether the curve is a good fit to the predicted mathematical relationship.

By manipulating the equation expressing this relationship, it is often possible to produce a linear graph for the variables.

Count rate is proportional to activity and to the number of undecayed nuclei remaining. If $N = N_0\mathrm{e}^{-\lambda t}$ then:

$$C = C_0\mathrm{e}^{-\lambda t}$$

If we take the logarithm of both sides of this equation:

$$\ln C = \ln C_0\mathrm{e}^{-\lambda t}$$

Rewriting this, using two of the laws of logarithms:

$$\ln C = \ln C_0 - \lambda t$$

Rearranging gives:

$$\ln C = -\lambda t + \ln C_0$$

Figure 3 shows the similarities between this equation and the general equation of a straight line,

$$y = mx + c$$

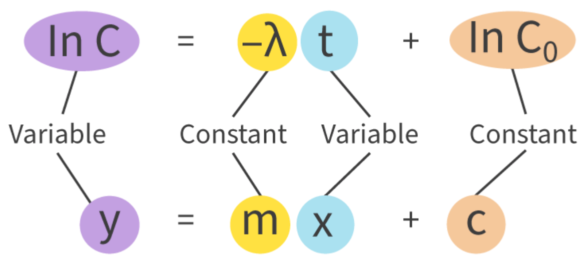

Figure 3. Comparing the equation of a straight line and the decay equation.

More information for figure 3

Student view

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The diagram illustrates a comparison between the equation of a straight line and a decay equation. On the left, it shows "ln C = -λt + ln C_0," where "ln C" and "t" are variables, and "-λ" and "ln C_0" are constants. The right side displays "y = mx + c," where "y" and "x" are variables, and "m" and "c" are constants. The diagram visually connects these components, emphasizing the similarities in structure between the linear and decay equations.

[Generated by AI]

Figure 3 shows that if $\ln C$ is plotted on the *y*-axis and *t* is plotted on the *x*-axis, the graph will be a straight line. The gradient of the line equals $-\lambda$, the negative of the decay constant. The *y*-intercept equals $\ln C_0$, the logarithm of the initial count rate.

The logarithm with base 10 can also be used, which gives:

$$\log C = -\lambda t + \log C_0$$

A graph of $\log C$ against *t* will also have $-\lambda$ as the gradient but the *y*-intercept will be $\log C_0$.

The decay law in terms of activity, or in terms of the number of undecayed nuclei, can be similarly expressed (and graphed as a straight line) using logarithms.

Worked example 4

The graph shows $\ln N$ against *t* for a pure sample of a radioactive nuclide that decays into a stable nuclide.

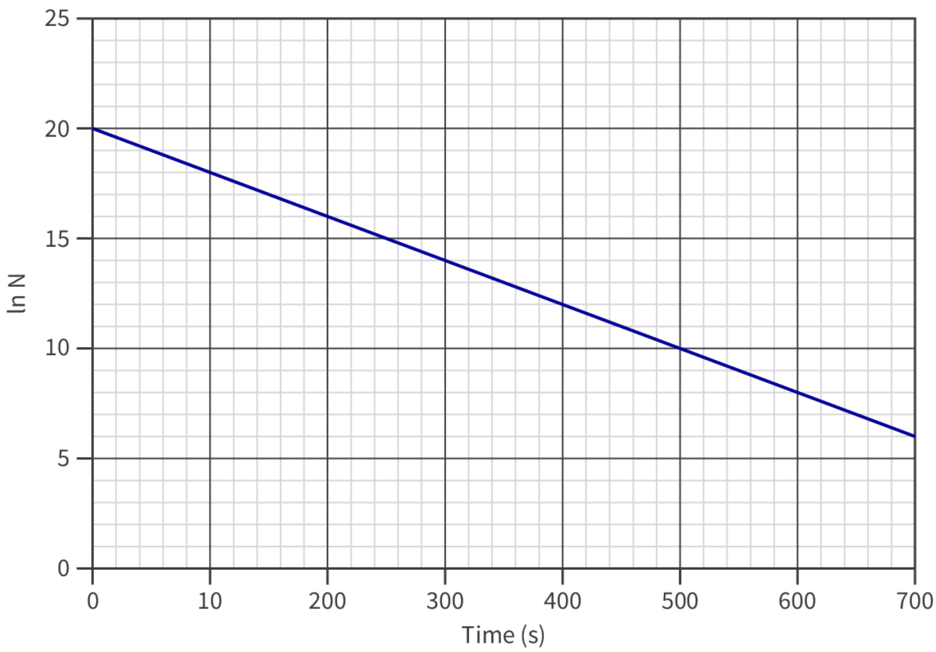

Figure 4. $\ln N$ against time for a radioactive nuclide.

More information for figure 4

Student view

The graph displays the natural logarithm of the number of unstable nuclei (ln N) plotted against time in seconds (s) for a radioactive nuclide. The x-axis represents time, ranging from 0 to 700 seconds, marked at intervals of 100 seconds. The y-axis represents ln N, with

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values ranging from 0 to 25, marked at intervals of 5 units. A downward trending line illustrates radioactive decay, starting at approximately ln N = 20 and decreasing steadily until it approaches ln N = 5 at around 600 seconds. This linear graph suggests a continuous decay over time with no inflection points, indicating a straightforward exponential decay process.

[Generated by AI]

Find:

1. the number of nuclei at the start
2. the decay constant of the radioactive nuclide.

1.

Solution steps	Calculations
Step 1: Write the radioactive decay law in terms of $\log N$ (by taking log of both sides).	$N = N_0 e^{-\lambda t}$ $\ln N = -\lambda t + \ln N_0$
Step 2: Read the *y*-intercept from the graph and equate it to $\log N_0$.	$\ln N_0 = 20$
Step 3: Take 10 to the power of each side.	$N_0 = 10^{20}$

2.

Solution steps	Calculations
Step 1: Choose two points on the graph, for example (0, 20) and (500, 10), and use them to find the gradient.	$\text{gradient} = \frac{\text{change in } y}{\text{change in } x} = \frac{10-20}{500-0} = -0.02$
Step 2: Equate the negative value of the gradient to λ.	$\lambda = 0.02\ \text{s}^{-1}$

Half-life and decay constant

It is useful to know the relationship between the half-life $T_{1/2}$ and the decay constant λ , since it is often the half-life that is known but it is the decay constant that appears in the radioactive decay equations.

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Substituting $t = T_{\frac{1}{2}}$ and $N = \dfrac{1}{2}N_0$ into $N = N_0\text{e}^{-\lambda t}$ gives:

$$\tfrac{1}{2}N_0 = N_0\text{e}^{-\lambda T_{1/2}}$$

Dividing both sides by N_0 gives:

$$\tfrac{1}{2} = \text{e}^{-\lambda T_{1/2}}$$

Using the fact that $\text{e}^{-\lambda T_{1/2}} = \frac{1}{\text{e}^{\lambda T_{1/2}}}$ gives:

$$\tfrac{1}{2} = \tfrac{1}{e^{\lambda T_{1/2}}}$$

$$2 = e^{\lambda T_{1/2}}$$

The inverse operation of e^x is $\ln x$ and so:

$$\ln 2 = \lambda T_{\frac{1}{2}}$$

Rearranging gives:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

The relationship between the half-life and the decay constant for a radioactive nuclide is shown in **Table 5**.

Table 5. The relationship between the half-life and the decay constant for a radioactive nuclide.

Equation	Symbols	Units
$T_{\frac{1}{2}} = \dfrac{\ln 2}{\lambda}$	$T_{\frac{1}{2}}$ = half-life	seconds, s (or other unit of time)
	λ = decay constant	per second, s^{-1} (or other reciprocal unit of time)

Note that the unit of λ is the reciprocal of the unit of $T_{\frac{1}{2}}$.

Decay constant and probability of decay

You may read in some places that for a given nuclide, the decay constant equals the probability that an undecayed nucleus will decay during the next unit of time. However, this cannot be correct because decay constants can be greater than one, which is not possible for a probability.

The decay constant λ is the constant of proportionality in the relationship $A = \lambda N$, where N is the number of undecayed nuclei in a pure radioactive source and A is the activity of the source.

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During a time interval Δt in which the number of nuclei that decay is ΔN, the average activity is $\frac{\Delta N}{\Delta t}$. This approximately equals the activity A at all times during the time interval if A does not fall significantly during this time.

Then $\frac{\Delta N}{\Delta t}$, and so:

$$\frac{\Delta N}{\Delta t} \approx \lambda N$$

or

$$\lambda \approx \frac{\Delta N}{N \Delta t}$$

$\frac{\Delta N}{N \Delta t}$ is the fraction of the nuclei that decay per unit time, which equals the probability that any given nucleus will decay during the next unit of time. This is a close approximation to λ if the activity does not change significantly during one unit of time – that is, if the unit of time is much shorter than a half-life. However, it is not a close approximation if the unit of time used for λ is close to or longer than the half-life.

For this reason, we usually use a time unit for the decay constant λ that is significantly shorter than the half-life. Then λ approximates the probability that any given nucleus will decay during the next unit of time.

Worked example 5

The radioactive nuclide bohrium-260 has half-life 35 ms.

1. Calculate the decay constant of bohrium-260, in ms^{-1}.
2. Write the decay constant in s^{-1}.
3. Comment on your answer to part 2.

1.

Solution steps	Calculations
Step 1: Write the equation relating half-life and decay constant.	$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$
Step 2: To calculate the decay constant in ms^{-1}, use half-life in ms.	$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{35} = 0.020\ \text{ms}^{-1}\ (2\ \text{s.f.})$

2.

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Solution steps	Calculations
Step 1: Convert the half-life to s.	$T_{\frac{1}{2}} = 35 \text{ ms}$ $= 0.035 \text{ s}$
Step 2: The calculated decay constant is now in s^{-1}.	$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}}$ $= \frac{\ln 2}{0.035}$ $= 20 \text{ s}^{-1} \text{ (2 s.f.)}$

3.

Solution steps	Calculations
Step 1: Consider the value of λ in part 2.	The probability of decay per second for a nuc cannot be greater than 1. The half-life of 35 m much shorter than 1 s, so although 20 s^{-1} is a correct value of λ it is not close to the probab of decay per second.

Work through the activity to check your understanding of the radioactive decay law.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Answer the following questions.

1. The age of once-living material can be measured using carbon dating. Living organisms absorb the radioactive isotope carbon-14 during their lifetime but this stops when they die. The carbon-14 then decays with a half-life of 5740 years. If living wood has activity of 250 Bq per kg, predict the activity of wood from a tree that died 500 years ago.
2. An ancient wooden canoe has activity of 150 Bq per kg. Estimate the time interval since the tree that the wood came from died.
3. Another type of radioactive dating, uranium-lead dating, can be used to measure the time since the formation of a common mineral called zircon,

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found in rocks. The graph in **Figure 5** shows how the natural logarithm of the number of undecayed nuclei in a sample of uranium-235 varies with time.

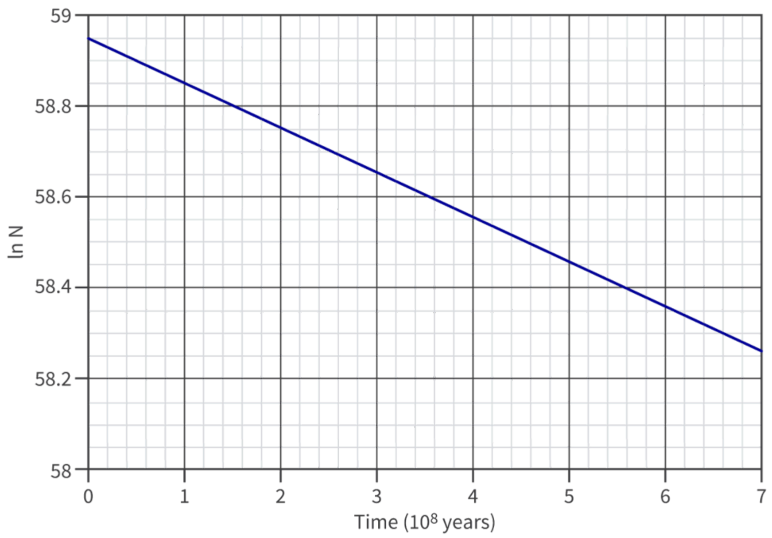

Figure 5. Graph of the natural logarithm of the number of undecayed nuclei against time for a sample of uranium-235.

More information for figure 5

The graph depicts the natural logarithm of the number of undecayed nuclei (ln N) of uranium-235 over time. The X-axis represents time measured in 10^8 years, ranging from 0 to 7. The Y-axis represents the natural logarithm of the number of undecayed nuclei, with values ranging from 58 to 59. A single descending diagonal line illustrates a decrease in ln N as time increases, indicating a continuous decay. The line starts at a high point on the Y-axis around 59 and gradually decreases, indicating a negative trend that corresponds to the decay process of uranium-235 over time.

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1.

(a) Estimate the number of undecayed nuclei at time = 0.
(b) Estimate the half-life of uranium-235.

1.

$$\lambda = \frac{\ln 2}{5740}$$
$$= 1.207 \times 10^{-4}\ \text{year}^{-1}$$

$$A = A_0 e^{-\lambda t} = 250 \times e^{-1.207 \times 10^{-4} \times 500} = 240\ \text{year}^{-1}\ (2\ \text{s.f.})$$

2.

$$\ln A = \ln A_0 - \lambda t$$

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$$t = \frac{\ln A \ - \ln A_0}{-\lambda}$$
$$= \frac{\ln 150 \ - \ln 250}{-1.207 \times 10^{-4}}$$
$$= 4200 \text{ years } (2 \text{ s. f. })$$

3. (a) $N = N_0 \mathrm{e}^{-\lambda t}$

$$\ln N = -\lambda t + \ln N_0$$

$$\ln N_0 \approx 58.95 \ (y\text{-intercept of graph})$$

$$N_0 \approx \mathrm{e}^{58.95}$$
$$\approx 4.00 \times 10^{25}$$

(b)

$$\lambda \approx \frac{58.95 - 58.30}{6.6 \times 10^8}$$
$$= 9.848 \times 10^{-10} \ (\text{gradient of graph})$$

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$
$$\approx \frac{\ln 2}{9.848. \times 10^{-10}}$$
$$= 7.0 \times 10^8 \text{ years } (2 \text{ s.f.})$$

5 section questions

Question 1

HL Difficulty:

An exponential decay curve is obtained if 1 activity ✓ , number of undecayed nuclei or background-corrected count rate is plotted against 2 time ✓ for a sample of a radioactive source.

The quantity plotted on the *y*-axis halves during each half-life. The half-life equals ln 2 divided by the 3 decay constant ✓ .

Accepted answers and explanation

#1 activity

#2 time

#3 decay constant

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General explanation

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You can add a general explanation here, if you want.

Question 2

HL Difficulty:

A pure sample of the radioactive nuclide polonium-210 decays into the stable nuclide lead-206. Both nuclides are solids.

Which statement is correct?

1. The mass of the sample halves in each half-life.
2. The number of nuclei of lead-206 doubles in each half-life.

1 neither 1 nor 2 ✓

2 1 only

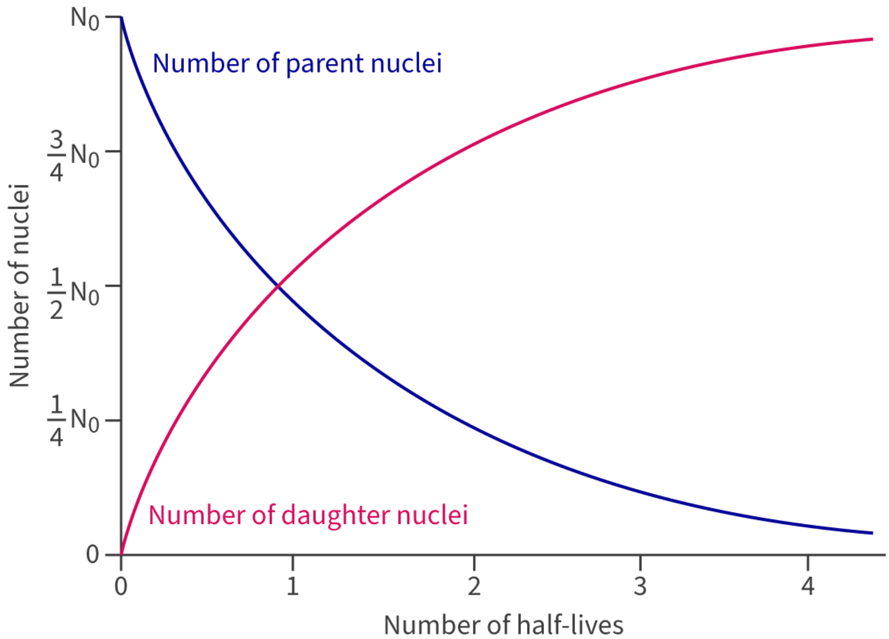
3 2 only

4 1 and 2

Explanation

The mass of the sample does not halve in each half-life, because the Po-210 nuclei that decay become Pb-206 nuclei, which do not have zero mass. So the sample does not lose half of its mass in each half-life.

The graph shows how the numbers of parent (Po-210) nuclei and daughter (Pb-206) nuclei change over time. (The number of daughter nuclei at any time equals *N* minus the number of undecayed parent nuclei remaining.)



More information

Student view

If the initial number of Po-201 nuclei is N_0 then $\frac{1}{2}N_0$ Po-210 nuclei decay during the first half-life. Therefore the number of Pb-206 nuclei increases from 0 to $\frac{1}{2}N_0$. This is not doubling.

During the second half-life, half of the remaining Po-210 nuclei decay. This is $\frac{1}{4}N_0$, and these become Pb-206 nuclei. So the number of daughter nuclei increases from $\frac{1}{2}N_0$ to $\frac{3}{4}N_0$. This is not doubling.

During the third half-life, $\frac{1}{8}N_0$ more Po-210 nuclei decay and the number of Pb-206 nuclei increases to $\frac{3}{4}N_0 + \frac{1}{8}N_0 = \frac{7}{8}N_0$, and so on.

Question 3

HL Difficulty:

Radium-223 has a half-life of 11.4 days.

An initial sample contains 2.6 × 10^{20} atoms of radium-223.

How many atoms of radium-223 are in the sample after 4.0 days?

Give your answer to an appropriate number of significant figures.

There are 1 2.0 ✓ × 10^{20} atoms

Accepted answers and explanation

#1 2.0

General explanation

$$T_{1/2} = 11.4 \text{ days}$$

$$N_0 = 2.6 \times 10^{20} \text{ atoms}$$

$$t = 4.0 \text{ days}$$

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

$$\begin{aligned} \lambda &= \frac{\ln 2}{T_{\frac{1}{2}}} \\ &= \frac{\ln 2}{11.4} \\ &= 0.0608 \text{ days}^{-1} \end{aligned}$$

$$\begin{aligned} N &= N_0 e^{-\lambda t} \\ &= 2.6 \times 10^{20} \times e^{-0.0608 \times 4.0} \end{aligned}$$

Question 4

HL Difficulty:

A small pure sample of a radioactive isotope contains 6000 atoms.

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The initial activity of the sample is 350 s^{-1}.

At a time *t* later, the activity is 35 s^{-1}.

Calculate the number of undecayed nuclei at time *t*.

600 ✓

Accepted answers

600

Explanation

$N = 6000 \text{ atoms}$

$A_0 = 350 \text{ s}^{-1}$

$A = 35 \text{ s}^{-1}$

$A = \lambda N$

initially $(t = 0)$: $A_0 = \lambda N_0$

at time t: $A = \lambda N$

$$\frac{A}{A_0} = \frac{N}{N_0}$$

$$\begin{aligned} N &= N_0 \frac{A}{A_0} \\ &= 6000 \times \frac{35}{350} \\ &= 600 \text{ (1 s.f.)} \end{aligned}$$

Question 5

HL Difficulty:

A student wants to find out the half-life, $T_{\frac{1}{2}}$, of a radioactive nuclide that decays into a stable nuclide.

They measure the background-corrected count rate, *C*, as a function of time, *t*, for a sample of the radionuclide.

Then they plot a graph of $\ln C$ against *t*.

Which statement is correct?

1 The gradient of the graph equals $-\lambda$ ✓

2 The *y*-intercept of the graph equals λ

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3 The y-intercept of the graph equals C_0

4 The negative reciprocal of the gradient equals $T_{\frac{1}{2}}$

Explanation

$C = C_0 e^{-\lambda t}$

$\ln C = \ln C_0 - \lambda t$

If $\ln C$ is plotted on the y-axis and t on the x-axis, the result is a straight line with y-intercept $\ln C_0$ and gradient $-\lambda$.

The gradient is $-\lambda$, but it is not the case that half-life $T_{\frac{1}{2}} = \frac{1}{\lambda}$.

The correct relationship is $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$.

E. Nuclear and quantum physics / E.3 Radioactive decay

Nuclear stability (HL)

E.3.14: Evidence for the strong nuclear force (HL) E.3.15: Stability of nuclides (HL) E.3.16: Range of constancy in the binding energy curve (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe evidence for the existence of the strong nuclear force.
- Explain the shape of the binding energy curve above a nucleon number of 60.
- Explain how the neutron to proton ratio relates to the stability of a nucleus.

Some isotopes are stable while others are not. Can we understand why? Is it possible to predict whether a nucleus with particular numbers of protons and neutrons will be stable or unstable?

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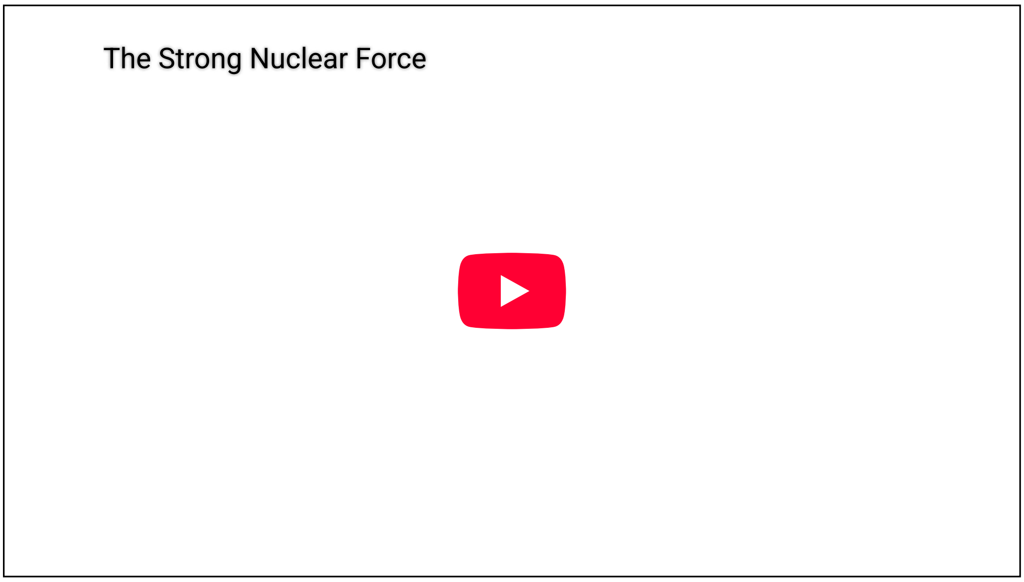
Figure 1. A radioactive sample.

Credit: unoL, Getty Images

Evidence for the strong nuclear force

The fact that atomic nuclei exist provides evidence for the strong nuclear force. Without this force to balance the electrostatic repulsion between protons, all nuclei would fly apart (except hydrogen-1, which contains only one proton).

Watch **Video 1** to find out more about the strong nuclear force. (The video uses pounds as a unit of force. 20 pounds is equivalent to about 90 N, and 70 pounds is equivalent to about 310 N.)



Video 1. The strong nuclear force.

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Neutron to proton ratio and stability

Figure 2 shows a graph of neutron number, N, against proton number, Z, for stable and unstable nuclides. Notice that the stable nuclides lie approximately along a line (which is not entirely straight but curves upwards slightly) – this is known as the line, or band, of stability.

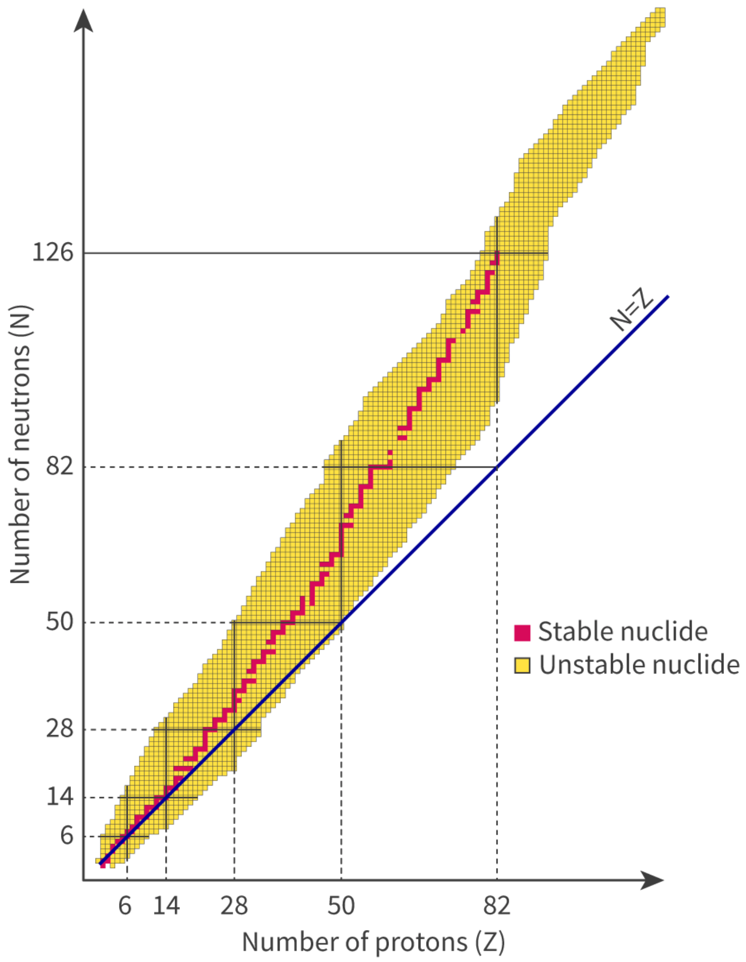

Figure 2. A graph of neutron number against proton number for stable and unstable nuclides.

More information for figure 2

The image is a graph showing the number of neutrons (N) on the vertical axis versus the number of protons (Z) on the horizontal axis. The horizontal axis is labeled "Number of protons (Z)" and ranges from 6 to 126, marked at intervals of 10 major divisions. The vertical axis is labeled "Number of neutrons (N)" and ranges from 6 to 126, marked similarly.

Within the graph, there is a dense band representing stable nuclides, which are shown in pink, running diagonally from the bottom-left to the top-right. This line is referred to as the line or band of stability and follows a path that curves gently upwards instead of being perfectly straight. There are also unstable nuclides shown in yellow, dispersed around the line of stability, indicating their deviation from the balanced ratio discussed.

There is an additional blue line labeled "N=Z" showing an equal number of neutrons and protons, present below the main band of stability. This line slopes upwards from the origin but deviates significantly from the path taken by the band of stability.

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Drag and drop the statements in **Interactive 1** to show whether they are true and false. Use information from **Figure 2** to help you.

True	False
As proton number increases, stable nuclides tend to have increasingly large ratios of proton number to neutron number	At proton numbers up to about 20, stable nuclides lie on or close to the N = Z line
For proton numbers up to about 20, the N:Z ratio of nuclides is close to 1:1	As proton number increases, stable nuclides tend to lie increasingly far above the N = Z line
Up to proton number 82, every element has at least one stable nuclide	Very large nuclei tend to have more neutrons than protons
	The N:Z ratio of the largest stable nuclide is approximately 3:2

Check

Interactive 1. Sort the statements into true and false.

We can see from the graph in **Figure 2** that stable nuclides lie on or close to the $N = Z$ line for proton numbers up to about 20. They lie increasingly far above the $N = Z$ line (in the region where $N > Z$) as proton number increases above 20.

Figure 3 shows the same graph as in **Figure 2**, but with colour coding showing the type of decay that each of the unstable nuclides undergoes. Some nuclides have more than one type of decay (the most probable type is shown).

What conclusions can be drawn about the relationship between N:Z ratio and type of decay?

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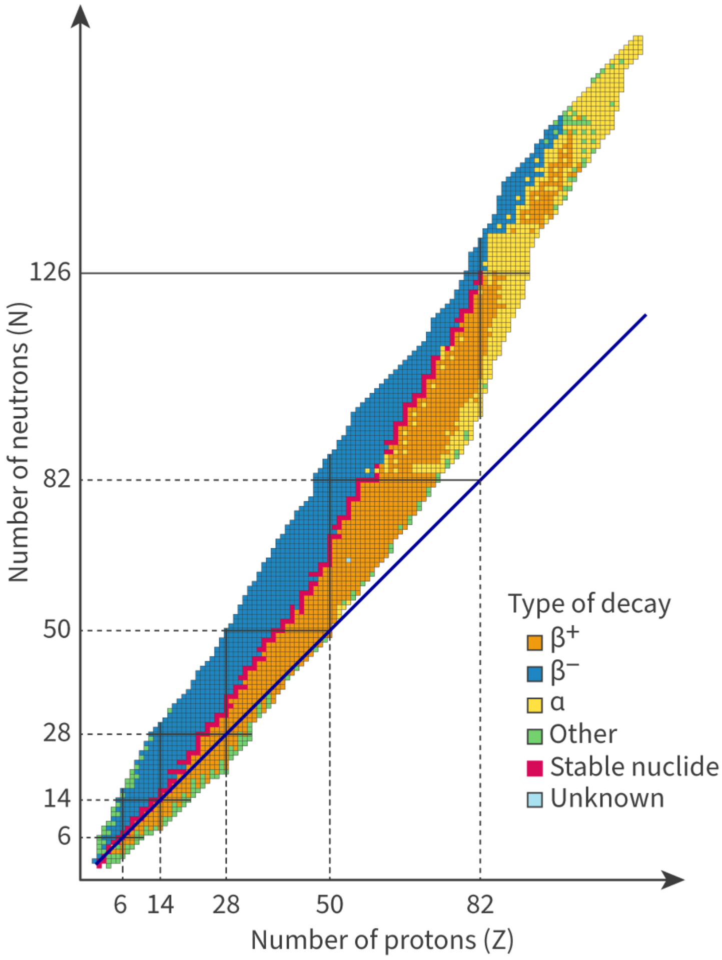

Figure 3. A graph of neutron number against proton number, showing the most probable type of decay (if any) of each nuclide.

More information for figure 3

The image is a graph depicting the relationship between neutron number (N) on the Y-axis and proton number (Z) on the X-axis. The X-axis is labeled 'Number of protons (Z)' with values ranging approximately from 6 to 126, and the Y-axis is labeled 'Number of neutrons (N)' with values ranging from 6 to 126. The graph is populated with colored regions representing different types of decay. There are five key decay types indicated by various colors: β+ (yellow), β- (blue), α (orange), Stable nuclide (pink), and Unknown (white) with an additional category labeled 'Other' in green. A diagonal line, marked in blue, crosses the graph, representing a reference or inflection. The data points form a band along the diagonal, with fluctuations indicating where certain decay types are more probable. The pattern indicates that stability varies with neutron to proton ratio, marking areas of instability where particular decay modes dominate.

[Generated by AI]

Range of strong nuclear force

We can see from **Video 1** that the range of the nuclear force is very short. Nucleons in a nucleus only experience significant attraction to their nearest neighbours. This means that in a nucleus that contains more than a few nucleons, nucleons on opposite sides of the nucleus do not exert attractive forces on each other (**Figure 4**).

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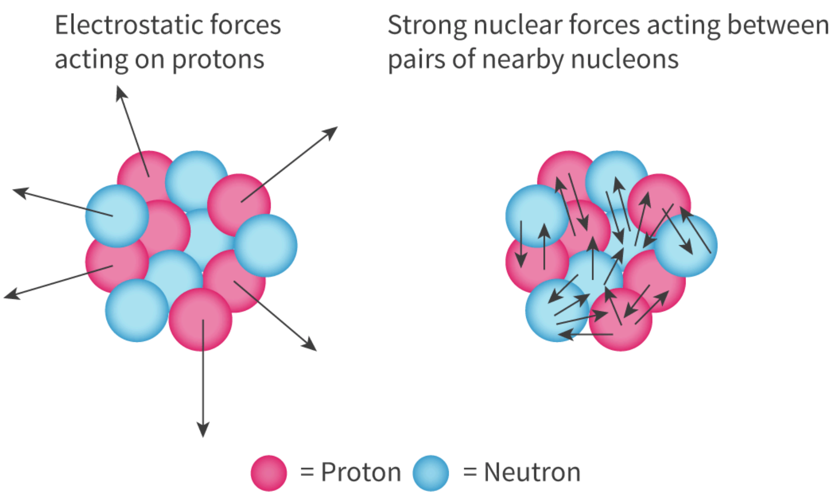

Figure 4. Electrostatic and strong nuclear forces on particles within a nucleus.

More information for figure 4

The image is a diagram illustrating electrostatic forces and strong nuclear forces within a nucleus. On the left side, it shows electrostatic forces acting on protons, represented by pink spheres, pointing outward with arrows indicating repulsion. On the right side, it depicts strong nuclear forces acting between pairs of nearby nucleons, which include both protons and neutrons (blue spheres). Arrows between these spheres indicate attractive forces holding them together. The diagram highlights the contrast between the repulsive electrostatic forces and the attractive strong nuclear forces that stabilize the nucleus. A legend at the bottom clarifies that pink spheres are protons and blue spheres are neutrons.

[Generated by AI]

The relationship between nucleon number and average binding energy per nucleon is shown in **Figure 5** (see also section E.3.4 (/study/app/physics/sid-423-cid-762593/book/binding-energy-and-mass-defect-id-46546/)).

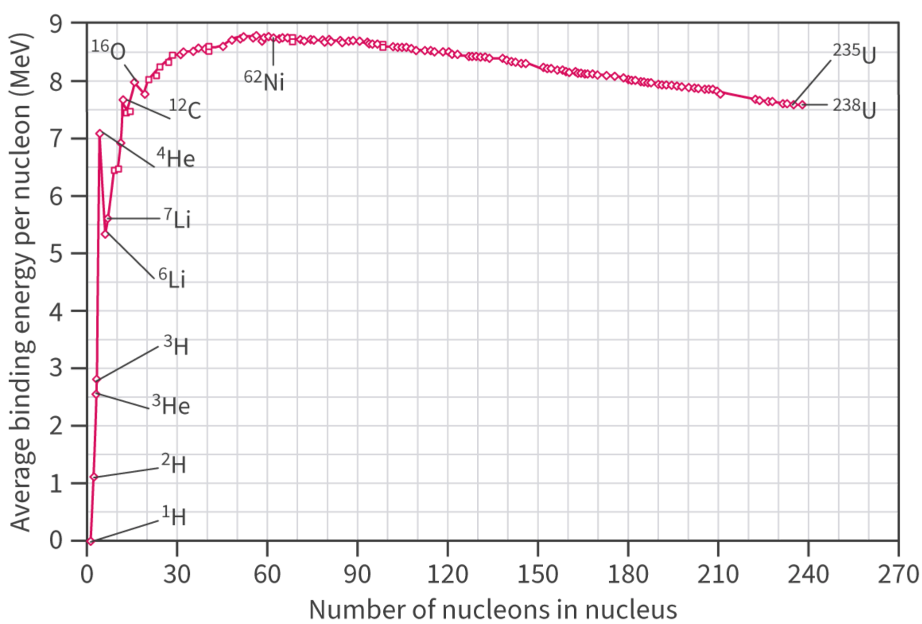

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Figure 5. A graph of average binding energy per nucleon against number of nucleons in the nucleus.

More information for figure 5

The graph displays the average binding energy per nucleon (in MeV) against the number of nucleons in the nucleus. The x-axis represents the number of nucleons, ranging from 0 to 270, and the y-axis represents the average binding energy per nucleon, ranging from 0 to 9 MeV. Significant data points are labeled with specific elements and their mass numbers, such as Hydrogen-3, Helium-4, Carbon-12, and Nickel-62. The graph starts with low binding energies at low nucleon numbers, showing a steep rise as the nucleon number increases. It then peaks and plateaus around 8 MeV for medium to large nuclei, with some small fluctuations, particularly notable around Nickel-62, which represents a relatively higher binding energy per nucleon.

[Generated by AI]

In relatively small nuclei (shown in the steeply rising part of the graph in **Figure 5**) every nucleon experiences a significant strong nuclear force towards every other nucleon. With each additional nucleon, the nucleons become more tightly bound, and so the average binding energy per nucleon increases.

For nucleon numbers above about 60, the binding energy decreases gradually with increasing nucleon number. The graph shows that the binding energy per nucleon decreases by less than 1.5 MeV from nucleon number 60 to 238.

As the number of protons in the nucleus increases, the average repulsive force on each proton always increases, because each proton is repelled by every other proton. The electrostatic force is long range, so protons on opposite sides of a large nucleus still repel each other significantly.

The strong nuclear force has a much shorter range. For nucleon numbers greater than around 60, the average number of neighbours near enough to experience the strong nuclear force does not change much as the nucleon number increases. Therefore, there is little increase in the average attractive force on each nucleon.

As a result, in large nuclei, the individual nucleons do not become much more tightly bound as the nucleon number increases. The neutron to proton ratio tends to become greater in stable nuclei as activity increases. Adding a neutron contributes to the attractive forces but not the repulsive forces in the nucleus. This partly compensates for the increasing electrostatic repulsion and the levelling off of the number of near neighbours, but not entirely.

For large nuclei, as the number of nucleons increases, the average binding energy per nucleon tends to decrease.

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Work through the activity to check your understanding of how the neutron to proton ratio relates to the stability of a nucleus.

Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:** Communication skills — Reflecting on the needs of the audience when creating engaging presentations
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

Look at this chart (https://people.physics.anu.edu.au/~ecs103/chart/), which shows naturally occurring and artificially created nuclides arranged by neutron number and proton number.

Double-click on the square for a nuclide to see an information panel. This shows the nuclide's discovery date, half-life and type of decay, and other properties beyond the scope of DP physics. (Some of the nuclides decay in ways that you are not required to know about for DP physics, for example, by emitting a single proton.)

Create a ten-minute 'guided tour' of the nuclides chart for SL students. The tour should explain what they are seeing as they are guided around different regions of the chart. It should include simple explanations of why each of the following types of decay are most common in particular regions of the chart: alpha, beta-plus and beta-minus. Write a script for the tour and/or record a video of it.

5 section questions

Question 1

HL Difficulty:

Which statement is correct?

1. All stable nuclides contain at least as many neutrons as protons.
2. There are no stable nuclides with nucleon number higher than 60.
3. Increasing the number of neutrons always makes a nucleus more stable.

1 none of the statements ✓

2 2

3 1 and 3

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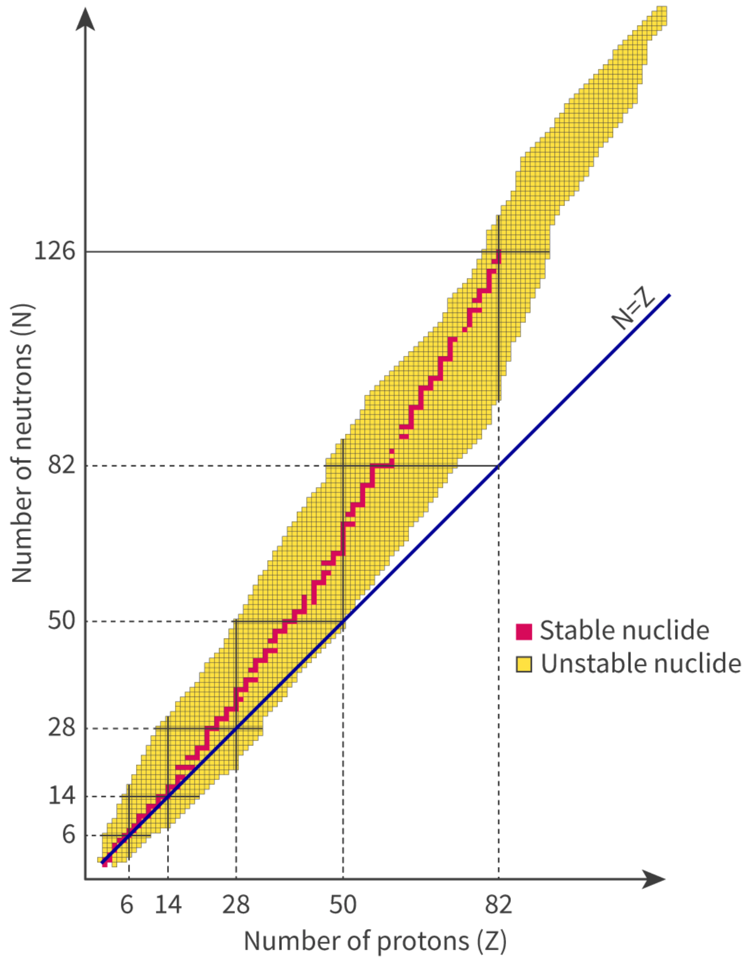
4 1, 2 and 3

Explanation

There exist stable nuclides with fewer neutrons than protons. One example is hydrogen-1, with one proton in the nucleus.



More information

The graph shows nuclides on a chart of neutron number against proton number. Many stable nuclides have nucleon numbers higher than 60.

Depending on its size and its *N*:*Z* ratio, increasing the number of neutrons can make a nucleus less stable. There are many examples in the graph where increasing *N* changes a nucleus from stable to unstable.

Question 2

HL Difficulty:

For stable nuclides, which of the following increases as nucleon number increases?

A = nucleon number
N = neutron number
Z = proton number

1 $\frac{A-Z}{Z}$ ✓

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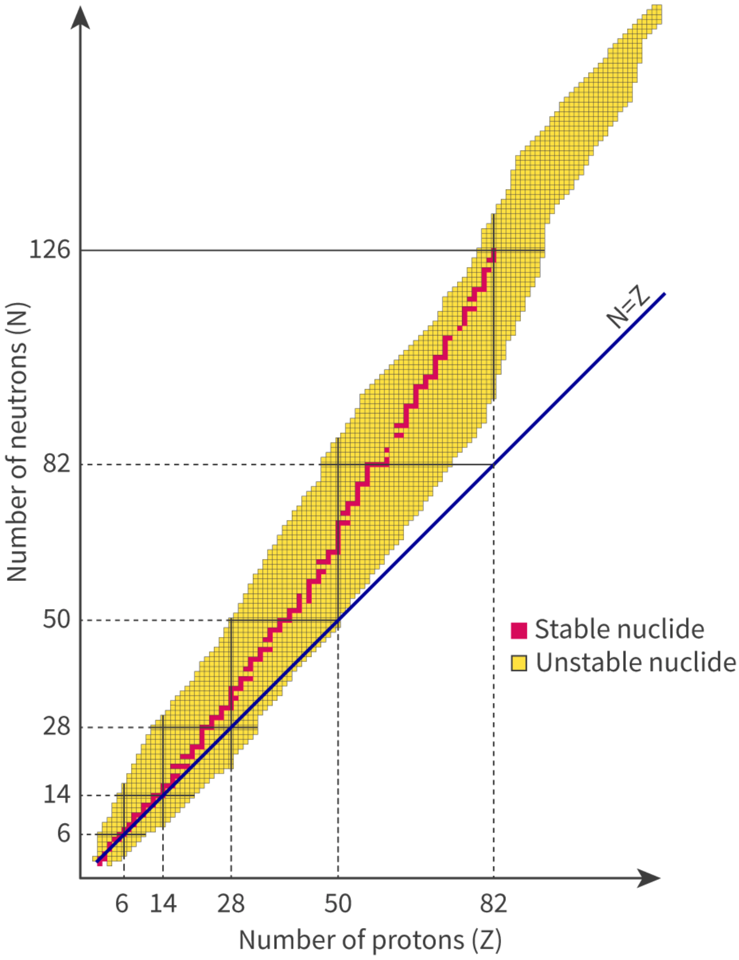
2 $\frac{N}{A-Z}$

3 $\frac{Z}{A-N}$

4 $\frac{Z}{A-Z}$

Explanation



More information

The graph shows that for stable nuclides, the ratio of $N{:}Z$ increases as the nuclides gain more nucleons. Therefore $\frac{N}{Z}$ also increases. N can be written as $A-Z$ (the difference between the nucleon and proton numbers), so $\frac{N}{Z} = \frac{A-Z}{Z}$, and $\frac{A-Z}{Z}$ for stable nuclides increases as nucleon number increases.

$\frac{Z}{A-Z}$ is the reciprocal of this so it decreases as nucleon number increases.

$\frac{N}{A-Z} = \frac{N}{N}$ and $\frac{Z}{A-N} = \frac{Z}{Z}$ so both equal 1 for any nuclide.

Student view

Question 3

HL Difficulty:

An unstable nucleus is above the $N = Z$ line on the chart of neutron number against proton number.

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Which of the following types of decay will result in a daughter nucleus that is closer to the $N = Z$ line?

1 beta-minus ✓

2 alpha

3 beta-plus

4 gamma

Explanation

In beta-minus decay, a neutron changes into a proton and a beta-minus particle (electron). This decreases the neutron number by 1 and increases the proton number by 1, so the daughter nucleus would be closer to the $N = Z$ line.

Alpha decay reduces N and Z by 2. If the ratio of N:Z in the parent nucleus is too heavily weighted towards N, subtracting the same number from both sides of the ratio would make this more extreme. The daughter nucleus would be farther from the $N = Z$ line.

In beta-plus decay, a proton changes into a neutron and a beta-plus particle (positron). This increases the neutron number by 1 and decreases the proton number by 1. The daughter nucleus would be farther from the $N = Z$ line.

Gamma decay does not affect the number of protons or neutrons in the nucleus, so it would not move the nucleus closer to the $N = Z$ line.

Question 4

HL Difficulty:

An unstable nucleus is below the $N = Z$ line on the chart of neutron number against proton number.

Which type of decay will result in a daughter nucleus that is closer to the $N = Z$ line?

1 beta-plus ✓

2 alpha

3 beta-minus

4 gamma

Explanation

In beta-plus decay, a proton changes into a neutron and a beta-plus particle (positron). This increases the neutron number by 1 and decreases the proton number by 1. The daughter nucleus would be closer to the $N = Z$ line.

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Alpha decay reduces N and Z by 2. If the ratio of N:Z in the parent nucleus is too heavily weighted towards Z, subtracting the same number from both sides of the ratio would make this more extreme. The daughter nucleus would be farther from the $N = Z$ line.

In beta-minus decay, a neutron changes into a proton and a beta-minus particle (electron). This decreases the neutron number by 1 and increases the proton number by 1, so the daughter nucleus would be farther from the $N = Z$ line.

Gamma decay does not affect the number of protons or neutrons in the nucleus, so it would not move the nucleus closer to the $N = Z$ line.

Question 5

HL Difficulty:

Which statement describes evidence for the existence and/or nature of the strong nuclear force?

1. Nuclei exist.
2. Nuclei attract electrons.
3. Above a nucleon number of 60, nuclei with higher nucleon numbers tend to have lower binding energies per nucleon.

1 1 and 3 ✓

2 1 only

3 2 only

4 2 and 3

Explanation

The existence of nuclei is evidence that there is an attractive force between nucleons that balances the repulsive electrostatic force between protons.

Negatively charged electrons are attracted to positively charged nuclei through the electrostatic force. This is not evidence for the strong force.

As the nucleon number increases above 60, the electrostatic repulsion experienced by each proton increases. This is not entirely compensated for by an increase in the attraction caused by the strong nuclear force. This is because, no matter how large a nucleus is, the electrostatic force acts between all protons in the nucleus, whereas the strong nuclear force acts between near neighbour nucleons only. The lower binding energies per nucleon of larger nuclei is evidence that the strong nuclear force has short range.

E. Nuclear and quantum physics / E.3 Radioactive decay

Summary and key terms

Student view

- Isotopes are atoms with the same number of protons but different numbers of neutrons. Nuclides are types of nucleus – some are stable and others are unstable. Unstable nuclides undergo radioactive decay.
- Four types of decay are alpha, beta-minus, beta-plus and gamma. In alpha decay, a nucleus emits an alpha particle consisting of two protons and two neutrons. In beta-minus decay, a nucleus emits a beta-minus particle (electron) and an antineutrino. In beta-plus decay, a nucleus emits a beta-plus particle (positron) and a neutrino. In gamma decay, a gamma photon is emitted. Alpha and beta decays cause a change from one element to another.
- All nuclear radiation is ionising. Alpha is the most ionising and the least penetrating. Gamma is the least ionising and the most penetrating. Beta is intermediate between alpha and gamma. The different penetrating abilities can be explained in terms of the energy loss due to ionisation.
- The activity of a radioactive source is the number of decays per unit time. The count rate of a source can be measured using a detector. Measured count rates can be corrected for background radiation (ionising radiation that is present in the environment).
- The decay of a nucleus is spontaneous and random. It is possible to predict the time it will take for the activity of a sample of a radioactive nuclide to halve, and this is called the half-life.
- Nucleons are held together in nuclei by the strong nuclear force. The binding energy of a nucleus is the work needed to split it into separate nucleons. The mass defect of a nucleus is the difference in mass between the nucleus and its separated nucleons. Energy and mass are equivalent according to the relationship $E = mc^2$, so a nucleus has less mass than the sum of its nucleons because it has lower energy.
- Larger values of average binding energy per nucleon are associated with greater stability of the nucleus. The average binding energy per nucleon increases relatively rapidly with nucleon number up to about 60, and then decreases much more slowly.

Higher level (HL)

- Alpha particles and gamma photons emitted during radioactive decay have discrete energies. This provides evidence that nuclei have quantised energies. Beta particles emitted during radioactive decay have a continuous spectrum of energies. This observation led to the prediction that another particle was also emitted during beta decay - the antineutrino in beta-minus decay, and the neutrino in beta-plus decay.
- The decay constant of a radioactive isotope can be calculated from its half-life using the formula $t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$. The decay constant does not exactly equal the probability of decay in unit time. The radioactive decay law, $N = N_0 e^{-\lambda t}$, relates the number of undecayed nuclei to the time since decay started and to the decay constant. It is an exponential decay relationship.
- The curve of average binding energy per nucleon against nucleon number decreases relatively gradually above a nucleon number of about 60. An underlying cause is the short range of the nuclear force compared with the electrostatic force.

- For stable isotopes, the N:Z ratio is close to 1:1 for proton numbers up to about 20, but the ratio becomes increasingly weighted towards N as the number of nucleons increases.

The concept diagram in **Figure 1** summarises the radioactive decay learning covered in this subtopic. You can download this as a full-page pdf using the button below the diagram.

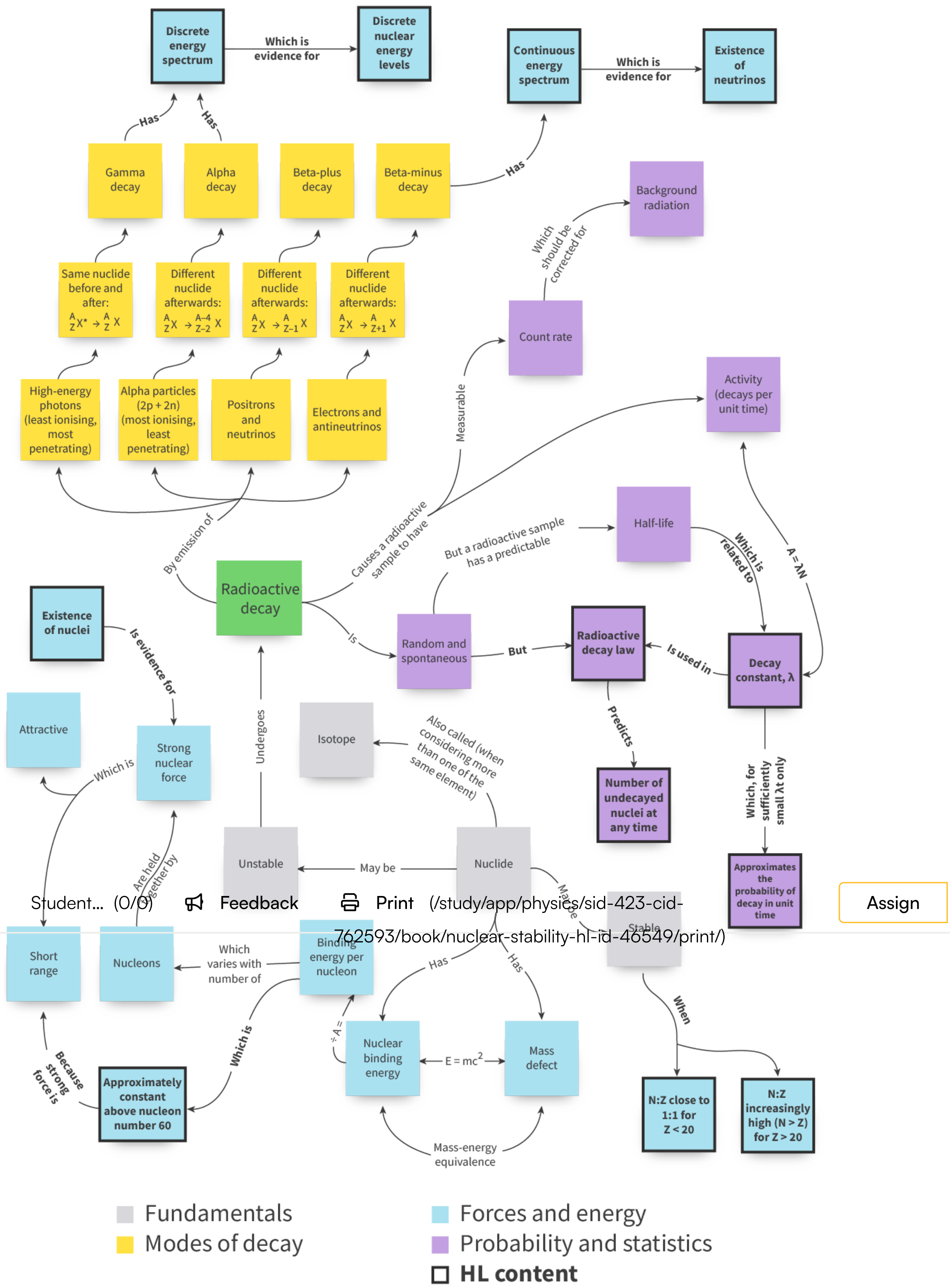

Figure 1. Concept diagram for radioactive decay.

More information for figure 1

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The diagram visually represents the concept of radioactive decay and includes various components and their interconnections. At the center is the "Radioactive decay" node, surrounded by related processes and elements. The diagram outlines different modes of decay, such as alpha decay, beta decay (with beta-plus and beta-minus), and gamma decay, each leading to different outcomes, like high-energy photon emission or positrons and neutrinos.

Connections are shown using arrows to indicate relationships and processes. For example, decay processes may lead to the same or different nuclide states after decay, affecting the subatomic particles emitted (such as alpha particles or electrons). The diagram shows dependencies and effects, such as how nuclear energy levels and energy spectra serve as evidence for the existence of neutrinos or other phenomena.

The diagram also includes terms like "Half-life," "Decay constant," and "Nuclear binding energy," each connected to nodes that describe their implications or related components, like isotopes, unstable nuclides, and stable elements. There is a clear differentiation of topics by color coding for fundamentals, modes of decay, forces and energy, probability and statistics, and HL content.

[Generated by AI]

Download image as PDF (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics E3.8 Concept diagram.8eee37bc4b2f104e0ad5.pdf)

Student view

Key terms

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Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. A key piece of evidence for the particle nature of light is the .
2. The is the number of radioactive decays per second in a sample.
3. A radioactive emission consisting of two protons and two neutrons is an particle.
4. An is a particle with very low mass and no charge which is emitted during beta-minus decay.
5. The is the work required to separate a nucleus into its constituent parts.
6. Ionising radiation that is present in the environment is called .
7. During decay an electron is emitted.
8. During decay a positron is emitted.
9. The is the number of ionising particles (including high-energy photons) detected per second by a detector of ionising radiation.
10. The is the constant of proportionality between the activity of a sample and the number of undecayed nuclei remaining in the sample.
11. A is a photon of electromagnetic radiation (short wavelength and high frequency).
12. The of a radioactive sample is the time it takes for the activity of the sample to halve.
13. is nuclear radiation that can cause ionisation of atoms.
14. are different types of atom of an element, with different numbers of neutrons but the same numbers of protons.
15. The difference between the mass of a nucleus and the total mass of its separated nucleons is called the
16. A is a particle with very low mass and no charge emitted during beta- plus decay.
17. A is any specific type of nucleus, where the type is determined by the numbers of protons and neutrons.
18. is the emission of one or more particles (which may include photons) by a nucleus, causing a change in the constituents and/or energy of the nucleus.
19. The is a force that attracts nucleons to each other in a nucleus.

gamma ray | mass defect | photoelectric effect | strong nuclear force
Radioactive decay | alpha | nuclide | Isotopes | Ionising radiation
count rate | background radiation | decay constant | neutrino | half-life
activity | beta minus | beta positive | binding energy | antineutrino

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Check

Interactive 1. Classify the Statements as True or False.

E. Nuclear and quantum physics / E.3 Radioactive decay

Checklist

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/checklist-id-46551/print/) Assign

What you should know

After studying this subtopic, you should be able to:

- Outline what isotopes are and that some isotopes are unstable.
- Describe the changes to the nucleus that occur during alpha decay, beta decay and gamma decay and use radioactive decay equations.
- Know that neutrinos and antineutrinos exist.
- Outline how background radiation affects the count rate of a source of nuclear radiation.
- Describe the penetrating and ionising abilities of alpha particles, beta particles and gamma rays.
- Explain that radioactive decay is random and spontaneous.
- Describe half-life and use values of half-life to describe the changes in activity and count rate during radioactive decay.
- Describe the strong nuclear force, nuclear binding energy and mass defect.
- Outline how binding energy per nucleon varies with nucleon number.
- Explain mass-energy equivalence and use the equation:

$$E = mc^2$$

Higher level (HL)

- Explain that the radiation spectrums for alpha decay and gamma decay are evidence for discrete nuclear energy levels.

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- Describe how the continuous spectrum of beta decay is evidence for the neutrino.
- Outline the decay constant and know that it only approximates the probability of decay in a unit time.
- Explain the radioactive decay law and use the equation:

$$N = N_0 e^{-\lambda t}$$

- Describe activity as the rate of decay and use the equation:

$$\begin{aligned} A &= \lambda N \\ &= \lambda N_0 e^{-\lambda t} \end{aligned}$$

- Describe the relationship between the decay constant and half-life and use the equation:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

- Describe evidence for the existence of the strong nuclear force.
- Explain the shape of the binding energy curve above a nucleon number of 60.
- Explain how the neutron to proton ratio relates to the stability of a nucleus.

Practical skills

Once you have completed this subtopic, go to Practical 9: Determining the half-life of random processes as a simulation of radioactive decay (/study/app/physics/sid-423-cid-762593/book/determining-the-half-life-of-random-processes-id-46753/) in which you will collect and analyse large data sets as a model for radioactivity.

E. Nuclear and quantum physics / E.3 Radioactive decay

Investigation

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/investigation-id-46552/print/) Assign

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
- **Approaches to learning:** Thinking skills – Applying key ideas and facts in new contexts
- **Time required to complete activity:** 1.5 hours
- **Activity type:** Group of 4

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Saturn's largest moon, Titan, has lakes, rivers and sometimes rain, but all of these are made of liquid methane. Observations have shown that Titan has some of the chemicals that were the early building blocks of life on Earth.

NASA is planning to send a vehicle to explore Titan. It will not be a rover, but it will be a drone, called Dragonfly (**Figure 1**). Flight is possible on Titan because it has a dense atmosphere – considerably denser than Earth's atmosphere.

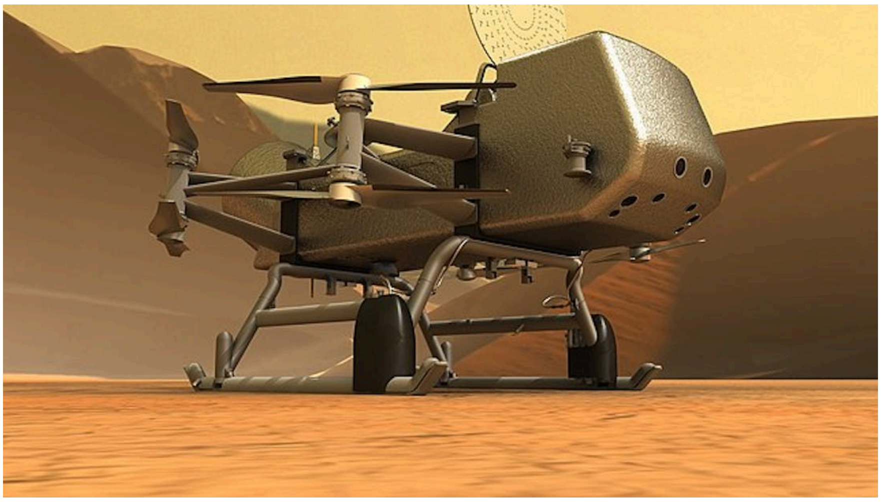

Figure 1. Artist's impression of NASA's Dragonfly drone.

Source: "Dragonfly spacecraft (https://commons.wikimedia.org/wiki/File:Dragonfly_spacecraft.jpg)" by NASAAPL is in the public domain

Like most drones, Dragonfly will have a rechargeable battery. Between flights, the battery will be recharged by a radioisotope thermoelectric generator (RTG) carried by Dragonfly. An RTG is a power supply that transfers thermal energy from radioactive decay to electrical energy. NASA intends to use plutonium-238 as the power source for Dragonfly's RTG. However, there is an international shortage of plutonium-238.

The key mission requirements are:

- It will take seven years for Dragonfly to be transported to Titan. It should then be active on Titan for at least three years.
- The electrical power supplied by the RTG must be at least 70 W throughout the mission.
- The mass of the radioactive source must be no more than 5 kg.

Your task

You are going to carry out research and make calculations to suggest an alternative radioactive isotope, instead of plutonium-238, to provide the power for Dragonfly.

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Make the following assumptions:

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- All gamma rays will escape without being absorbed, and so their energy will not be transferred usefully.
- All the energy from any other type of radioactive emission is available to the RTG as thermal energy.
- The efficiency of an RTG at transferring thermal energy to electrical energy is 6%.
- The source will consist of an initially pure sample of your chosen nuclide.

Each person in your group should choose one of the following nuclides to research using the internet:

- americium-241
- curium-244
- polonium-210
- strontium-90.

Study skills

When you carry out an internet search, some search engines show 'typical' questions and answers based on your search. Note that the 'answers' may not be correct or relevant.

It is good practice to establish where key pieces of information come from. When taking information from a website, check whether the author is likely to be knowledgeable and reliable. Would you trust a university physics department? Would you trust the anonymous writer of a science blog?

- For your chosen nuclide, write down its decay equation, and the decay, if any, of the daughter nuclide.

Higher level (HL)

Describe where your chosen nuclide lies relative to the *N*-*Z* curve of nuclides, and give a possible reason for the particular type of decay it undergoes.

- Write down the mass per atom for the nuclide and the energy released per decay (not including gamma).
- Calculate the activity needed for the for the RTG to provide the minimum power required.
- Using the method outlined below, determine the minimum number of atoms the nuclide sample should initially contain, so that at the end of the mission the RTG will still be providing (just) enough power.

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Use **Interactive 1** to estimate the number of atoms needed. Input the half-life in seconds for

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your chosen nuclide by using the two sliders, c and d, to set the two parts of this number in standard form.

Experiment with different initial activities (using the two sliders, p and q, to set the two parts of this number in standard form). You need to find a suitable initial activity to ensure that the activity after ten years is still as high as the mission requires (but no higher).

Interactive 1. Calculating the number of atoms required for a radioactive source with a given initial activity.

More information for interactive 1

This simulation demonstrates how to estimate the number of atoms required for a specific mission by analyzing the half-life of a chosen nuclide and adjusting its initial activity. Using this interactive, the simulation provides a step-by-step approach to determine the correct quantity of radioactive material to maintain the necessary activity levels over a ten-year period.

The graph represents the activity of a substance measured in becquerels (*Bq*) over a period of time (in years), showing a typical exponential decay curve. As time progresses, the activity decreases significantly, following a characteristic decay rate. The y-axis represents the activity of the substance in becquerels (*Bq*), ranging from 0 to 14,000,000 Bq. The

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activity decreases as time progresses, reflecting the decay of the radioactive substance. The x-axis represents time in years, ranging from 0 to 10 years. This indicates how the substance's activity changes over the course of a decade.

This interactive allows users to manipulate various parameters that affect the activity and decay of the substance. The sliders at the bottom of the screen represent several variables: *c*, *d*, *p*, *q*, and T_{half}, which are used to calculate the decay of the substance. The slider *c* adjusts the coefficient in standard scientific notation. The slider *d* adjusts the exponent in standard form. The slider *p* controls the coefficient in standard notation. The slider *q* sets the exponent in standard form.

The half-life, T_{half}, is determined by the equation:

$T_{half} = c \times 10^{d}$,

Here in this case, it equals 1×10^{9} s. The initial activity, A_0, is calculated as

$A_0 = p \times 10^{q}$, which gives 7.93×10^{16} Bq. The initial number of atoms, N_0, is given as 1.14×10^{26} Bq.

For the case shown in the image, the half-life is set to 1×10^{9}s, and the initial activity is 7.93×10^{16} Bq. The graph shows the activity starting at 7.93×10^{16} Bq and decreasing over time.

The value of N_0 is determined by using the equation $A_0 = \lambda N_0$. Here, λ is the decay constant, and N_0 is the initial number of atoms. The decay constant can be found by knowing the half-life period using the equation:

The curve follows an exponential decay, which is a typical behavior for radioactive substances. As time progresses, the substance loses its radioactivity, which is demonstrated visually by the decline in the curve's height on the graph.

Higher level (HL)

Carry out a calculation to confirm the result from **Interactive 1**. Show your working.

- When you have found the initial number of atoms needed, you need to convert this to a mass of the nuclide. Use **Interactive 2** to carry out this calculation. Type in the nucleon number of the nuclide, then type in the initial number of atoms needed. The interactive calculates the mass in grams of the nuclide.

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Interactive 2. Calculator of the mass of an isotope, given its nucleon number and number of atoms.

More information for interactive 2

This interactive helps users explore the relationship between the **mass of a substance** and the **number of atoms** it contains. It allows users to input two key values: **the nucleon number of a nuclide** and **the initial number of atoms needed**, and it then calculates the total mass in grams. This provides a hands-on approach to understanding how atomic properties scale up to macroscopic quantities.

The **nucleon number** represents the total count of **protons and neutrons** in an atom's nucleus, giving an estimate of an individual atom's mass. In this case, the interactive uses a **nucleon number of 250**, meaning each atom in the sample consists of 250 nucleons. The number of atoms is expressed in **scientific notation** as 7.93×10^8, emphasizing the **large quantities** typically encountered when working with atomic-scale particles. The resulting **mass in grams**, also displayed in scientific notation as 1.983×10^{11} g, represents the total weight of the given number of atoms.

To explore these values further, users can input different nucleon numbers and atom counts in the interactive to see how the total mass changes with varying parameters. This allows users to engage in practical calculations, offering a hands-on way to explore fundamental concepts in atomic physics and chemistry. The interaction demonstrates the power of scientific notation in simplifying large-scale calculations and shows how atomic and molecular properties are linked to everyday quantities like mass.
The interactive is useful for calculating the total mass of an object based on its nucleon number and number of atoms, providing a simple way to understand how atomic properties relate to macroscopic quantities like mass.

- As a group, discuss your findings and select a suitable nuclide for the mission. You will need to consider the required mass for each nuclide (is it above the maximum allowed mass of 5 kg?) Which nuclide needs the lowest mass? What factors affect the mass required for a particular nuclide?

Reflection

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/).

- Why are some isotopes more stable than others?
- 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?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

Once you submit your response, you won't be able to edit it.

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Submit

Rate subtopic E.3 Radioactive decay

Help us improve the content and user experience.

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