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The big picture

? **Guiding question(s)**

- In which form is energy stored within the nucleus of the atom?
- How can the energy released from the nucleus be harnessed?
- How can the risks of nuclear power plants be balanced against the benefits?

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 1942 in Chicago, physicist Enrico Fermi and his team built the world's first nuclear reactor in a squash court. They had a vision, which was to harness the power of nuclear fission. This is a phenomenon where atoms split apart and release massive amounts of energy.

Fermi and his team created a structure made of graphite blocks and uranium that they called a 'pile' (**Figure 1**). They inserted a control rod made of cadmium to regulate the fission reaction, which was initiated by a single neutron.

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Figure 1. The first nuclear reactor — Chicago Pile 1.

Source: Racquets Court under West Stands of Stagg Field, University of Chicago (https://commons.wikimedia.org/wiki/File:1
22_p.m,_December_2,_1942._Place,_Racquets_Court_under_West_Stands_of_Stagg_Field,_University_of_Chic
NARA-_542144.tif) by U.S. National Archives and Records Administration is in the public domain

The pile began to heat up as the uranium atoms split apart and released energy in the form of heat. This was the world's first controlled nuclear fission reaction, which led to the development of nuclear power.

Watch **Video 1** for more background into Fermi's experiment and discussion about its implications.

Video 1. The world's first nuclear reactor.

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Nuclear power plants use nuclear fission to generate electricity for millions of people around the world. However, we need to manage the products of nuclear fission carefully as they are dangerous.

Does the energy provided by nuclear fission contribute to the solution for climate change? If so, what actions do we need to take to ensure nuclear fission is safe and used ethically?

International Mindedness

Nuclear power plants are located in many different countries, but the consequences of a disaster at a nuclear power plant can affect the whole world, such as the one in Japan at Fukushima Daiichi nuclear power plant during 2011. The World Association of Nuclear Operators (WANO (https://www.wano.info/)) is an international organisation that helps ensure that nuclear power is used safely and responsibly around the world.

Discuss with your classmates:

- How does WANO maintain its influence around the world?
- Are there any limitations on an international organisation like WANO?

Prior learning

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

- Energy density of fuels (see subtopic A.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43083/)).
- Binding energy and mass defect (see subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/)).
- Mass-energy equivalence as given by $E = mc^2$ (see subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/)).

E. Nuclear and quantum physics / E.4 Fission

Nuclear fission

E.4.1: Energy released in fission E.4.2: Chain reactions in nuclear fission

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Learning outcomes

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

- Describe nuclear fission and determine the energy released.
- Explain the role of chain reactions in nuclear fission.
- Describe how nuclear fission can be neutron-induced or spontaneous.

In the last century it was often predicted that energy would become too cheap to meter. Advances in technology combined with revolutionary new ideas have transformed the energy sector, but abundant, clean energy for all remains out of reach, for now. Nuclear fission has been heralded as an answer to climate change, yet is seen by some as posing greater environmental risks than existing energy generation means. What is nuclear fission, and why does it divide opinion?

Nuclear fission

There are two types of nuclear reaction:

- Fission – a large nucleus splits into two or more smaller nuclei.
- Fusion – two or more small nuclei join into a larger nucleus.

Figure 1 shows fission and fusion. Nuclear fusion is covered in subtopic E.5 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44745/).

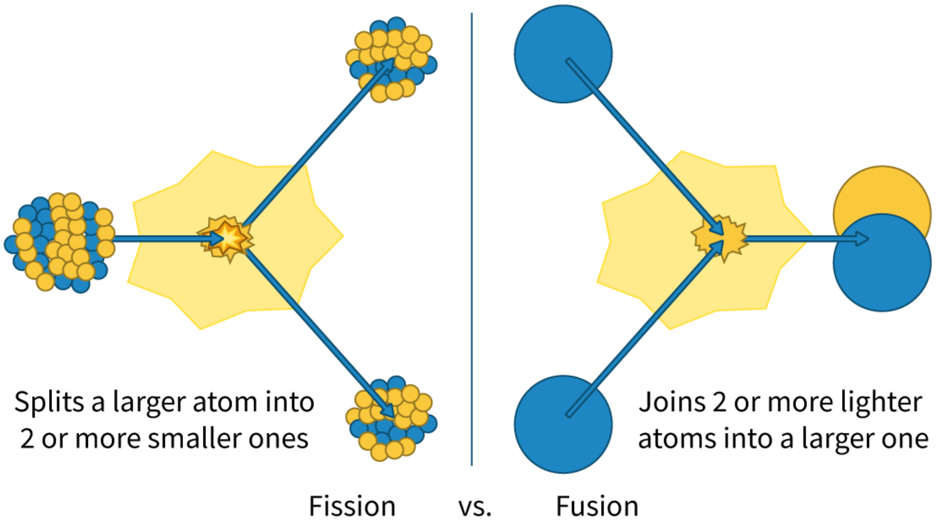

Figure 1. The difference between nuclear fission and nuclear fusion.

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More information for figure 1

The image is a diagram that illustrates the differences between nuclear fission and nuclear fusion. On the left side, it shows the nuclear fission process where a large nucleus, such as uranium-235, absorbs a neutron and splits into smaller nuclei, such as barium-144 and krypton-89, along with the release of energy and additional neutrons. On the right side, it depicts the nuclear fusion process where two smaller nuclei, such as isotopes of hydrogen, combine to form a larger nucleus, like helium, releasing energy in the process. Both sides of the diagram show energetic reactions with arrows indicating the flow from reactants to products. The diagram visually distinguishes between the splitting and combining of nuclei in the two processes.

[Generated by AI]

A uranium-235 nucleus undergoes nuclear fission by absorbing a neutron and becoming uranium-236. Uranium-236 is highly unstable and rapidly splits into barium-144, krypton-89 and some neutrons.

Interactive 1 shows the nuclear equation for the fission of uranium-235. Put whole numbers into the boxes to balance the equation.

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-46447/print/) Assign

$$^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + \boxed{}\,{}^{1}_{0}n$$

0 1 2 3 4 5 6 7 8 9

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Interactive 1. Balancing the equation for the fission of uranium-235.

More information for interactive 1

This is a drag-and-drop interactivity that presents a nuclear fission reaction involving uranium-235. The objective is to complete the missing numbers in the nuclear equation by dragging the correct numerical tiles into the blank boxes. By absorbing a neutron, a uranium-235 nucleus can undergo nuclear fission and transform into uranium-236. Due to its extreme instability, uranium-236 immediately separates into barium-144, krypton-89, and a few neutrons.

The interactivity shows the nuclear equation starting on the left with a neutron labeled as, $^{1}_{0}n$, which combines with uranium-235 labeled $^{235}_{92}U$. The result of this initial interaction is a compound nucleus labeled $^{236}_{92}U$, which then undergoes fission.

There are four empty boxes that the user must fill using the digit tiles provided at the bottom of the image. The first box, between uranium-235 and uranium-236, represents the mass number of the neutron that initiates the reaction. The second box is located before $^{144}_{56}Ba$, represents the number of barium nuclei produced. The third box appears before $^{89}_{36}Kr$, represents the number of krypton nuclei produced. The fourth and final box is before the neutron product $^{1}_{0}n$, and this indicates how many neutrons are released in the process.

At the bottom of the interactivity, there are digit tiles labeled 0 through 9 arranged horizontally. These are draggable and can be placed into the empty boxes above. The user can drag any of the digits and drop them into the appropriate blank space to complete the equation. Once all boxes are filled, the user can press the "Check" button at the bottom left to validate their answers. This interactivity reinforces the conservation of mass number and atomic number in nuclear reactions, as users must ensure the sum of mass numbers and atomic numbers on both sides of the equation match.

Solution:

First box: 1

Second box: 1

Third box: 1

Fourth box: 3

By actively engaging with the reaction, users gain a clearer understanding of how nuclear equations are balanced and how chain reactions can be initiated and sustained.

Making connections

In a nuclear equation, the mass number and atomic number are conserved. This is essential for balancing the equation. Other conservation laws also apply, such as conservation of electric charge (subtopic D.2 (/study/app/physics/sid-423-cid-

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762593/book/the-big-picture-id-44743/)) and conservation of momentum (subtopic A.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-43136/)).

Nuclear energy

Nuclear fission releases large amounts of energy. The energy released per unit mass of fuel is much greater for nuclear fuel than for other types of fuel. **Table 1** shows the energy per unit mass for different fuels (source: whatisnuclear.com (http://whatisnuclear.com)).

Table 1. Energy per unit mass for different fuels.

Fuel	Energy per unit mass (MJ/kg)
Coal	30
Oil	42
Natural gas	53.5
Lithium	43
Uranium-235	79 390 000

Note the following points from subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/):

- The total mass defect is proportional to the total change in binding energy.
- Mass defect and binding energy are related by the equation $E = mc^2$.
- Fission reactions result in a move up the binding energy curve when heavier elements split into lighter nuclei.

Study skills

Mass defect is the difference between the mass of a nucleus and the sum of the masses of its individual protons and neutrons. For nuclear reactions, instead of calculating the mass defect of each nuclei, it is quicker to calculate the mass difference before and after the fission reaction.

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Worked example 1

One possible way in which a uranium-235 nucleus undergoes nuclear fission is:

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$$

(a) Calculate the mass defect, Δm, in unified atomic mass units (u).

(b) Calculate the energy released in MeV for the reaction.

(c) Determine the energy released in MJ for 1 kg of U-235.

Mass of a neutron = 1.008665 u

Mass of a U-235 nucleus = 235.043930 u

Mass of a Ba-144 nucleus = 143.922941 u

Mass of a Kr-89 nucleus = 88.917632 u

(a)

$$\begin{aligned}\Delta m &= \text{mass of reactants} - \text{mass of products}\\ &= (m_{\text{neutron}} + m_{\text{U-235}}) - (m_{\text{Ba-144}} + m_{\text{Kr-89}} + 3m_{\text{neutron}})\\ &= (1.008665\,\mathrm{u} + 235.043930\,\mathrm{u}) - \\ &\quad [143.922941\,\mathrm{u} + 88.917632\,\mathrm{u} + (3 \times 1.008665\,\mathrm{u})]\\ &= 0.186027\,\mathrm{u}\end{aligned}$$

A positive mass defect means that the reaction will release energy.

(b)

$$1\,\mathrm{u} = 931.5\ \mathrm{MeVc^{-2}}$$

$$\begin{aligned}\Delta E &= \Delta mc^2\\ &= (0.186027\,\mathrm{u} \times 931.5\ \mathrm{MeV\ c^{-2}})\mathrm{c}^2\\ &= 173.3\ \mathrm{MeV}\end{aligned}$$

(c)

Molar mass is how many grams per mole for an atom of an element (subtopic B.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44289/)).

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One mole of U-235 atoms is approximately 235 g.

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Calculate the number of moles in 1 kg of U-235:

$$\text{number of moles, } n = \frac{1000}{235}$$
$$= 4.26 \text{ mol}$$

Uranium atoms in 1 kg of U-235:

$$\begin{aligned}\text{number of atoms, } N &= nN_A \\ &= 4.26 \times 6.02 \times 10^{23} \\ &= 2.56 \times 10^{24} \text{ atoms}\end{aligned}$$

From (b), one uranium nucleus releases 173.3 MeV

Total energy released for 1 kg of U-235:

$$\begin{aligned}E &= 2.56 \times 10^{24} \times 173.3 \text{ MeV} \\ &= 444 \times 10^{24} \text{ MeV}\end{aligned}$$

$$1\text{eV} = 1.6 \times 10^{-19} \text{ J}$$

$$\begin{aligned}E &= 444 \times 10^{24} \text{ MeV} \\ &= 444 \times 10^{24} \times (1.6 \times 10^{-19}) \text{ MJ} \\ &= 7.104 \times 10^{7} \text{ MJ} \\ &= 7.1 \times 10^{7} \text{ MJ (to 2 s.f.)}\end{aligned}$$

Note that molar mass is referring to the U-235 atom while the energy in (b) is referring to the U-235 nucleus, i.e. the mass of the electrons is ignored.

Does the answer to (c) in **Worked example 1** verify the data for uranium-235 in Table 1? Yes, the answer of 7.1×10^7 MJ is relatively close to the given value of 7.9×10^7 MJ.

The energy released during a nuclear fission reaction varies depending on the daughter nuclei, which may have different binding energies. For example, rather than U-235 becoming Ba-144 and Kr-89, it may become xenon-140 (Xe-140) and strontium-94 (Sr-94) instead.

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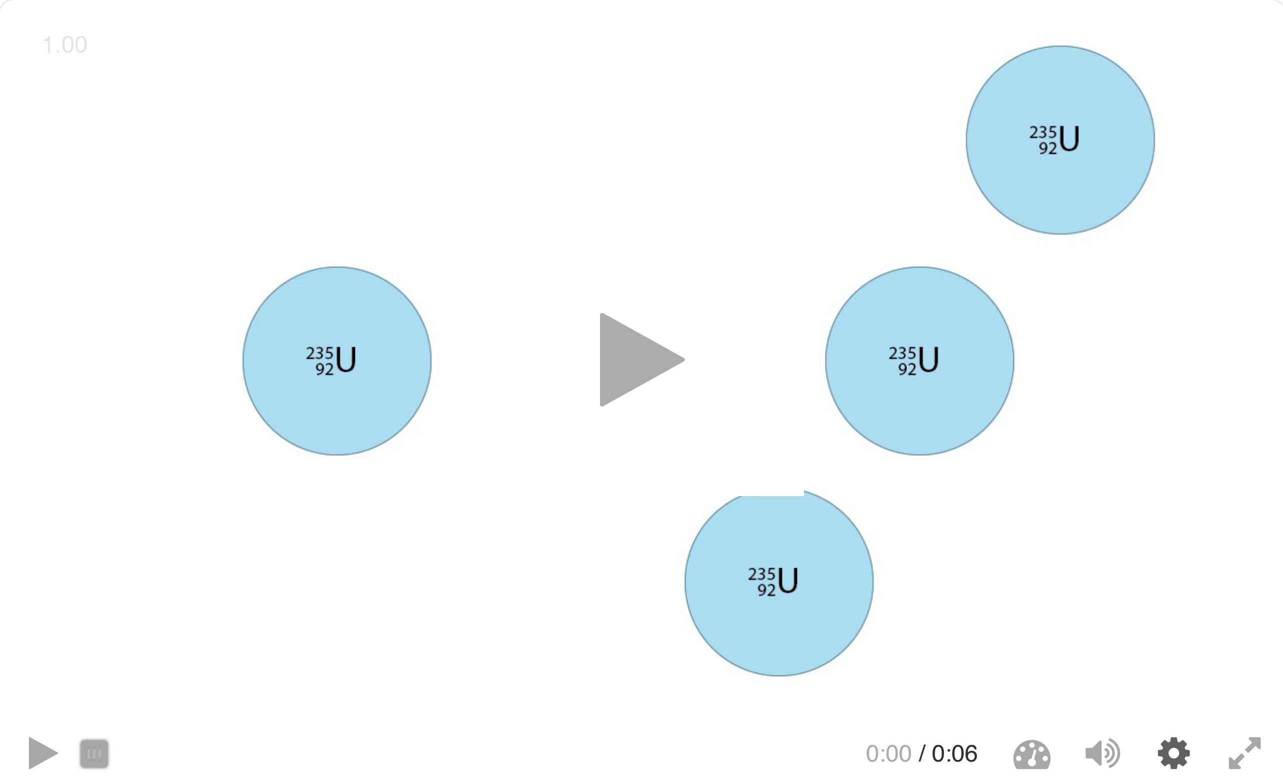
Pay attention to the units that you are required to state your answer in. The conversion of 1 u = 931.5 MeV c^{-2} is useful. When using this unit of mass with $E = mc^2$, the unit of E is in MeV. Note that c^{-2} cancels out c^2 in the equation.

Chain reactions

The neutrons produced by nuclear fission can hit other uranium-235 atoms, causing further fission reactions, which release yet more neutrons. This self-sustaining reaction is known as a chain reaction.

Interactive 2 shows how this chain reaction can be self-sustaining. You will learn more about how to create a sustainable chain reaction in the activity at the end of the section.



Interactive 2. Nuclear Fission Leading to a Chain Reaction.

More information for interactive 2

The interactive is a video that illustrates a chain reaction in nuclear fission using animated visuals. The video begins with several large blue circles labeled as uranium-235 (235 92 U), representing the fissionable nuclei. A smaller gray circle labeled as 1 0 n (neutron) is shown approaching one of the uranium nuclei. Upon collision, the uranium nucleus undergoes fission, splitting into two smaller nuclei—barium-144 (144 56 Ba) and krypton-89 (89 36 Kr)—both labeled in blue. Simultaneously, three new neutrons, each labeled as 1 0 n, are emitted from the reaction.

These emitted neutrons are then seen moving outward, striking other nearby uranium-235 nuclei. As each of these nuclei undergoes fission, they too split into krypton and barium while releasing more 1 0 n neutrons. This sets off a

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chain reaction as the newly released neutrons continue to collide with additional uranium-235 atoms. The animation clearly depicts how each neutron labeled 1 0 n contributes to sustaining the reaction, which rapidly grows with each cycle.

During fission, not all the neutrons released will impact upon a suitable nuclei, such as U-235. In order to maintain the chain reaction, the concentration of U-235 in the uranium fuel has to be high enough in comparison to the concentration of U-238. The process of increasing the concentration of U-235 (the fissile isotope) in nuclear fuel is called fuel enrichment.

In addition, the neutrons will disperse in random directions. If the amount of fissile isotope is too small, then not enough of the neutrons will be absorbed to sustain the chain reaction. The critical mass is the minimum amount of the fissile isotope needed to sustain a nuclear chain reaction (**Figure 2**). The management of fuel enrichment and critical mass is crucial for the safe and effective operation of nuclear power plants. You do not need to know about fuel enrichment or critical mass in DP physics.

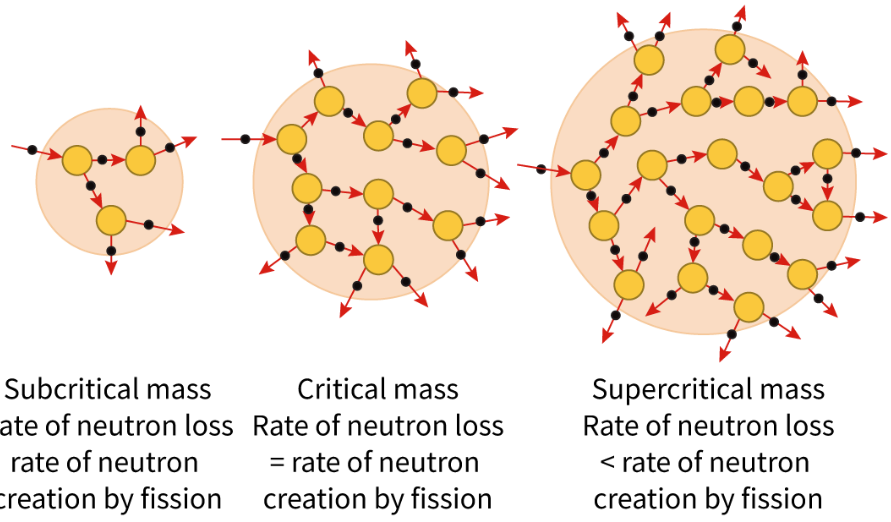

Figure 2. How critical mass sustains a chain reaction.

More information for figure 2

The diagram illustrates the concept of critical mass in a nuclear chain reaction. It contains three images progressively showing the effect of increasing the amount of fissile isotope.

1. The first image depicts a small circle with a few yellow circles (representing neutrons) connected by black dots, illustrating a limited chain reaction with many neutrons escaping, indicated by red arrows pointing outward.
2. The second image shows a larger circle with more yellow circles and black dots, indicating a more successful chain reaction, with some neutrons still escaping, as shown by fewer red arrows.

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3. The third image displays the largest circle, illustrating a successful nuclear chain reaction where the critical mass is reached. Most of the neutrons are captured, with only a few red arrows pointing outward.

The progression visualizes how increasing the mass of isotopes affects the sustainability of a chain reaction.

[Generated by AI]

Neutron-induced fission and spontaneous fission

The nuclear fission that we have looked at so far is neutron-induced fission. This is when a neutron collides with a nucleus and the neutron is absorbed, causing the nucleus to become unstable and split into two smaller daughter nuclei. A large amount of energy is released as gamma rays along with the kinetic energy of the two daughter nuclei and the neutrons.

Figure 3 shows the neutron-induced fission of a uranium-235 nucleus.

Some heavy elements are so unstable they can undergo spontaneous fission. This is where a nucleus splits into two roughly equal daughter nuclei without absorbing a neutron first (**Figure 3**).

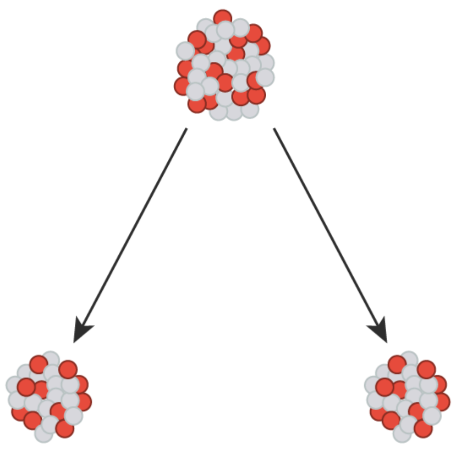

Figure 3. Spontaneous fission in heavy, unstable nuclei.

More information for figure 3

The diagram shows a process of spontaneous nuclear fission. At the top-center is a cluster of spheres representing a heavy nucleus. Two arrows point downward from this nucleus to two similar clusters, indicating the splitting into two daughter nuclei. The clusters symbolize the nuclei of atomic particles breaking apart. The diagram represents the

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splitting process without showing any labeled particles or specific reactions.

[Generated by AI]

For example, an unstable nucleus of Plutonium (Pu-239) splits into Palladium (Pd-112), Cadmium (Cd-124) and three neutrons. The nuclear equation is:

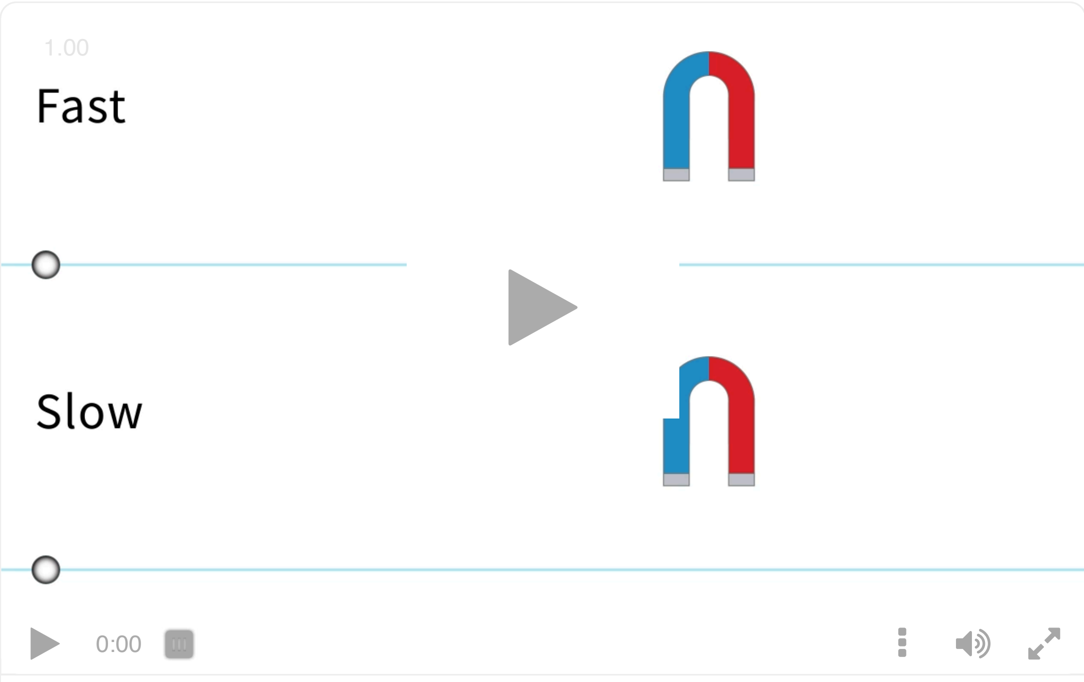
$$^{239}_{94}\text{Pu} \rightarrow \, ^{112}_{46}\text{Pd} + \, ^{124}_{48}\text{Cd} + 3^{1}_{0}\text{n}$$

Neutron-induced fission using chain reactions are used in nuclear power plants to produce energy. Spontaneous fission is not reliable or stable enough to be used in nuclear power plants.

Concept

A common misconception is that high-speed neutrons collide with uranium nuclei to induce fission. However, in reality, it is slow neutrons that are the most effective in inducing fission.

Look at **Interactive 3**. It shows a metal ball bearing moving past a magnet.



Interactive 3. Analogy of Fast- and Slow-moving Neutrons.

More information for interactive 3

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This interactive video illustrates a concept where a metal ball bearing moves past a magnet at two different speeds: fast and slow. The first part of the video shows the ball bearing moving quickly past the magnet, and the second part shows the ball moving slowly.
The animation illustrates the difference in how fast- and slow-moving metal balls interact with a magnet, using it as an analogy for neutron capture in nuclear fission. In the top half of the screen, a metal ball labeled “Fast” moves swiftly toward a U-shaped magnet. As it approaches, the ball continues along its path and fails to attach to the magnet, indicating that the magnetic attraction is not strong enough to alter its motion significantly. This visual represents how fast-moving neutrons in nuclear reactions often escape without being absorbed by atomic nuclei.
In contrast, the bottom half of the screen shows a metal ball labeled “Slow” moving at a much slower speed toward a similar magnet. As this slower-moving ball nears the magnet, it is pulled in and sticks firmly to the magnet’s pole. This outcome highlights how slower-moving neutrons, like the ball bearing, are more effectively captured due to the increased time spent near the attractive force — in this case, magnetic force as an analogy for the nuclear force. The comparison emphasizes that slower neutrons have a higher likelihood of being absorbed by nuclei, which is essential for sustaining a chain reaction in nuclear fission.

The animation on the left shows the metal ball bearing moving quickly past the magnet. The animation on the right shows the ball bearing moving slowly past the magnet. Which ball bearing (fast or slow) is attracted by the magnet?

A slow moving neutron is captured by the nucleus due to the strong nuclear force (subtopic D.2 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44743/)). A fast moving neutron may pass the nucleus without being absorbed.

Work through the activity in the next section (/study/app/physics/sid-423-cid-762593/book/activity-nuclear-fission-simulation-id-46449/) to explore nuclear fission chain reactions.

5 section questions ^

Question 1

SL HL Difficulty:

Which of the following statements best describes neutron-induced fission?

1 A nucleus absorbs a slow-moving neutron, and splits into daughter nuclei and neutrons. ✓

2 A nucleus absorbs a fast-moving neutron, and splits into daughter nuclei and neutrons.

3 A nucleus splits into two roughly equal daughter nuclei without absorbing a neutron.

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4 A nucleus is smashed by a fast-moving neutron and splits into two smaller nuclei.

Explanation

In neutron-induced fission, a slow-moving neutron is absorbed by a nucleus, and the nucleus splits into two smaller daughter nuclei and some neutrons.

Question 2

SL HL Difficulty:

The nuclear equation shows a neutron-induced fission reaction. Balance the equation to determine the number X.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{96}_{37}\mathrm{Rb} + {}^{\mathrm{X}}_{55}\mathrm{Cs} + 3{}^{1}_{0}\mathrm{n}$$

137 ✓

Accepted answers

137

Explanation

The sum of the mass numbers must be equal on both sides of the equation:

$$235 + 1 = 96 + \mathrm{X} + 3{*}1$$

$$236 = 99 + \mathrm{X}$$

$$\mathrm{X} = 137$$

Question 3

SL HL Difficulty:

Which of the following nuclear equations, A B, C or D, shows spontaneous fission?

A. $^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\mathrm{He}$

B. $^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{8}_{4}\mathrm{Be} + \gamma$

C. $^{236}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{143}_{57}\mathrm{La} + {}^{90}_{35}\mathrm{Br} + 3{}^{1}_{0}\mathrm{n}$

D. $^{254}_{98}\mathrm{Cf} \rightarrow {}^{118}_{46}\mathrm{Pd} + {}^{132}_{52}\mathrm{Te} + 4{}^{1}_{0}\mathrm{n}$

1 D ✓

2 A

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3 B

4 C

Explanation

A is alpha decay and not spontaneous fission, which should produce roughly equal daughter nuclei.

B is nuclear fusion, because two smaller nuclei join to make a larger nucleus.

C is neutron-induced fission, as there is a neutron on the left side of the equation.

D is spontaneous fission because the nucleus splits into two roughly equal daughter nuclei, without absorbing a neutron.

Question 4

SL HL Difficulty:

A nuclear fission 1 chain ✓ reaction occurs when a neutron is absorbed by a heavy nucleus, causing it to split into two smaller daughter nuclei and releasing 2 neutrons ✓ , which are absorbed by other heavy nuclei, causing further nuclear 3 fission ✓ reactions.

Accepted answers and explanation

#1 chain

#2 neutrons

#3 fission

General explanation

During a chain reaction, neutrons produced by the fission of a nucleus are absorbed by other nuclei, causing further fission reactions, and releasing more neutrons.

Question 5

SL HL Difficulty:

The nuclear equation shows one way in which a uranium-235 nucleus can undergo nuclear fission.

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$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2^{1}_{0}\mathrm{n}$$

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Determine the energy released by this fission reaction. Give your answer to 4 significant figures.

Mass of a neutron = 1.008665 u
Mass of a U-235 nucleus = 235.043930 u
Mass of a Xe-140 nucleus = 139.921656 u
Mass of a Sr-94 nucleus = 93.915360 u

The energy released is 1 184.7 ✓ MeV.

Accepted answers and explanation

#1 184.7

General explanation

$$\begin{aligned}\Delta m &= (m_{\text{neutron}} + m_{\text{U-235}}) - (m_{\text{Xe-140}} + m_{\text{Sr-94}} + 2m_{\text{neutron}}) \\ &= (1.008665 + 235.043930) - [139.921656 + 93.915360 + (2\times 1.008665)] \\ &= 0.198249\,\text{u}\end{aligned}$$

$$1\,\text{u} = 931.5\ \text{MeVc}^{-2}$$

$$\Delta E = \Delta mc^2$$

$$\begin{aligned}\Delta E &= (0.198149\,\text{u} \times 931.5\,\text{MeVc}^{-2})\ \text{c}^2 \\ &= 184.6689\ \text{MeV} \\ &= 184.7\ \text{MeV}\ (4\ \text{s.f.})\end{aligned}$$

E. Nuclear and quantum physics / E.4 Fission

Activity: Nuclear fission simulation

E.4.1: Energy released in fission E.4.2: Chain reactions in nuclear fission

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Activity

Part A

Work through this activity to explore the process of nuclear fission.

- **B learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 10 minutes
- **Activity type:** Pair activity

1. Select the 'Fission: One Nucleus' tab.
2. Press the red button on the neutron gun to shoot a neutron. What happens when a neutron is absorbed by the U-235 nucleus?

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The neutron is absorbed by the U-235 nucleus and becomes a U-236 nucleus, which is unstable and fission occurs. The U-236 nucleus splits into two daughter nuclei and three neutrons.

3. Click 'Reset Nucleus' and press the red button to shoot another neutron. In which direction do the products of fission move after the fission reaction occurs?

The daughter nuclei and the neutrons move in different directions. The two daughter nuclei always move in opposite directions (conserving momentum before and after fission).

4. Why is the uranium nucleus more likely to absorb a neutron rather than a proton?

The nucleus consists of many protons and neutrons. As protons are positively charged, there is a repulsive electric force between an approaching proton and the protons in the nucleus.

Part B

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning: Thinking** skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Look at the simulation.

1. Select the 'Chain Reaction' tab.
2. Use the sliders on the right-hand side to set the initial number of U-235 nuclei to 100 and the initial number of U-238 nuclei to 0.
3. Press the red button to shoot a neutron. Describe what happens? Do you think there is a chain reaction?

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The neutron hits a U-235 nucleus, which undergoes nuclear fission. The three neutrons from that fission reaction hit other U-235 nuclei, which in turn undergo nuclear fission. There is a chain reaction because the first fission reaction produces three neutrons. These neutrons then either hit other U-235 nuclei (producing more neutrons) or leave the screen.

4. Click ‘Reset Nuclei’.
5. Set the initial number of U-238 nuclei to 100 and the initial number of U-235 nuclei to 0 using the sliders.
6. Press the red button to shoot a neutron. What happens this time? Is there a chain reaction?

When the neutron is absorbed by U-238, it becomes U-239. U-239 is stable and does not undergo fission. There are no neutrons produced to hit other U-238 nuclei so there is no chain reaction.

7. Click ‘Reset Nuclei’.
8. Set the initial numbers of U-235 and U-238 nuclei to each of the rows in **Table 1.** For each experiment, fire in a neutron and once the reaction is complete count how many U-235 nuclei remain. Convert this to a percentage of the original amount and record the result in the Trial 1 column. Repeat the experiment a further two times but move the nozzle of the neutron gun before each trial. Record your results.

Table 1. Experimental data from nuclear fission simulation.

Number of U-235 nuclei	Number of U-238 nuclei	% of U-235 nuclei remaining		
		Trial 1	Trial 2	Trial 3
100	0			
75	25			
50	50			
25	75			
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9. Which ratios of U-235 to U-238 created a chain reaction? Why do you think it is important to change the direction of the initial neutron between trials?
10. The most common naturally occurring uranium ore is composed of U-238 (99.27%) and U-235 (0.72%). Looking at your data from the experiment, what can be done to uranium ore to make a fission chain reaction possible?

Increase the concentration of U-235 compared to the concentration U-238 before using uranium as a fuel, through a process known as fuel enrichment.

E. Nuclear and quantum physics / E.4 Fission

Nuclear power plants

E.4.3: Control rods, moderators, heat exchangers and shielding E.4.4: Nuclear fission products and management

Learning outcomes

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

- Understand the roles of control rods, moderators, heat exchangers and shielding in a nuclear power plant.
- Describe the properties of the products of nuclear fission and how they are managed.

Watch **Video 1** to see which locations on the Earth have the most background radiation (see subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/)).

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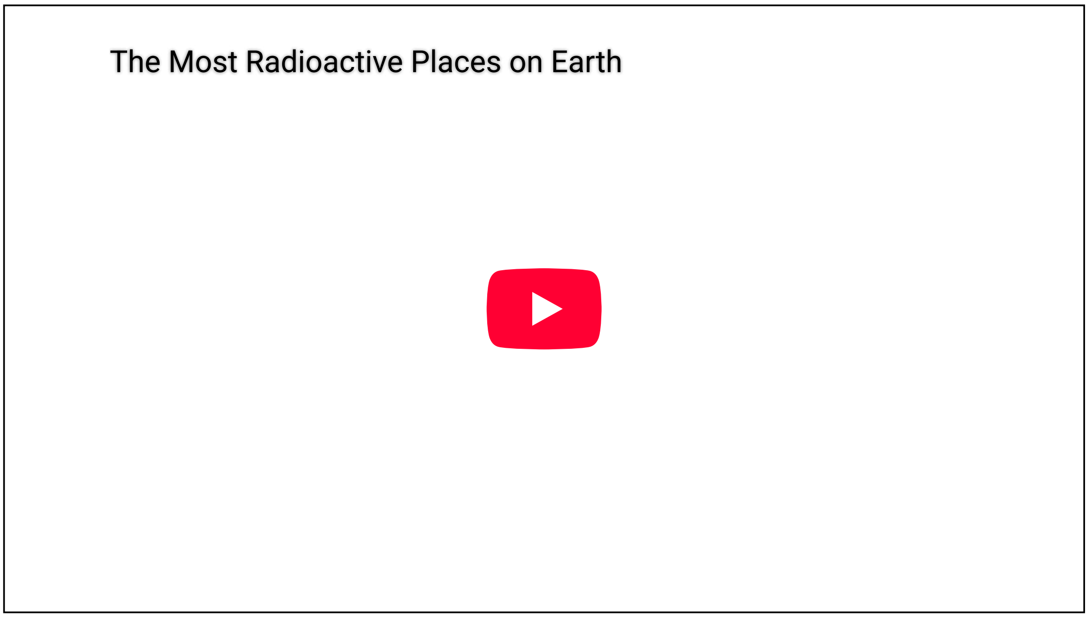

Video 1. Background radiation across the world.

The radiation produced by nuclear power plants only contributes a small amount to the total background radiation. However, there are other risks associated with nuclear power plants. How should we evaluate the risks and benefits of nuclear power?

International Mindedness

Nuclear power is a topic that goes beyond the scope of science and technology to encompass a range of social, political and environmental issues. The management of nuclear fuel, from extraction to disposal, must take into account the long-term impact on communities and the environment. The nuclear power plant disasters in Chernobyl, Ukraine, in 1986 and Fukushima, Japan, in 2011 highlight the critical importance of international cooperation in managing nuclear risks and promoting safety standards.

The effects of nuclear disasters can have far-reaching consequences. Countries need to work together to develop effective regulations and strategies to prevent and manage such incidents. This requires collaboration between governments, international organisations, and scientific communities to ensure the safe and responsible use of nuclear technology. By prioritising international cooperation and promoting a global perspective on nuclear power, we can ensure a sustainable and safe energy future for generations to come.

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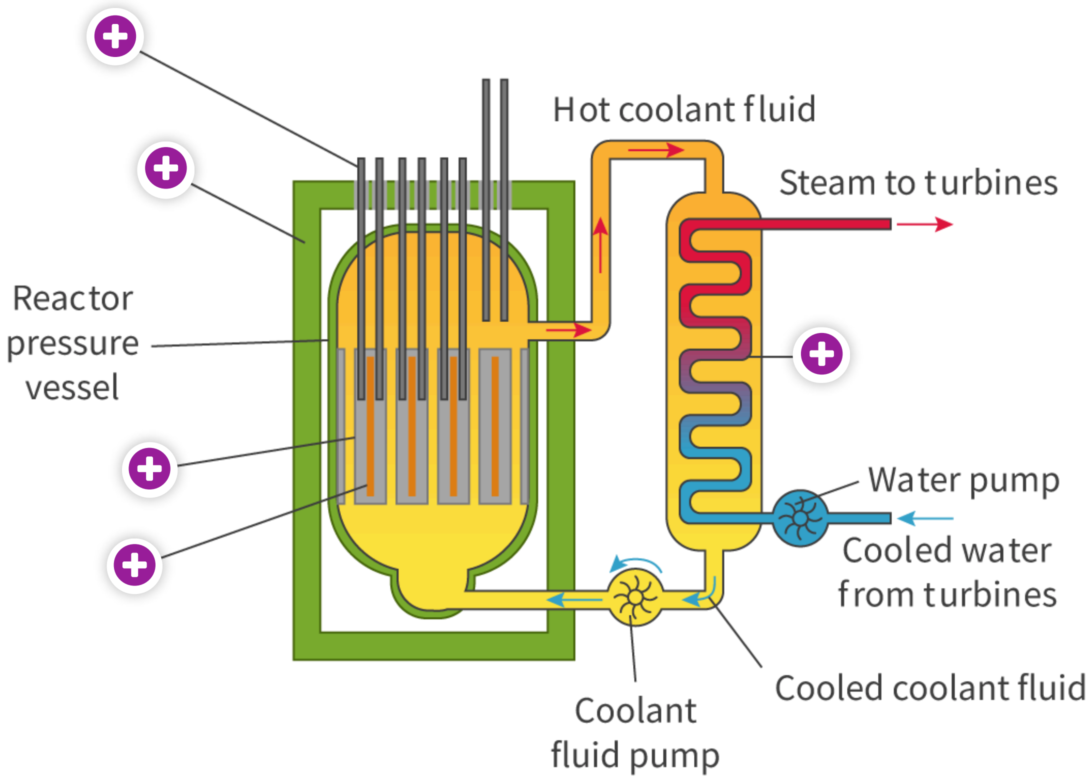
The nuclear reactor

Nuclear power plants and fossil fuel power plants generate electricity. They both use heat to produce steam, which drives a turbine to generate electricity. However, the way they generate heat is different. Fossil fuel power plants burn coal, oil or natural gas to generate heat, while nuclear power plants use nuclear fission. Nuclear fuel contains nuclear potential energy, which is converted to the kinetic energy of the products (the daughter nuclei and especially the neutrons, which travel very fast). When many fission events occur, this kinetic energy can be considered as thermal energy in the reactor. It is this thermal energy which, through the heat exchanger, can be delivered to the turbines in order to do useful work.

Click on the hotspots in **Interactive 1** to find out about the parts of a nuclear reactor in a nuclear power plant.



Interactive 1. Diagram of a Nuclear Reactor.

More information for interactive 1

This interactive presents a clear diagram of a nuclear reactor with several labeled components and interactive hotspots for further explanations. The diagram highlights the key elements of the reactor system and allows users to interact with each section for more detailed information. The interactive includes plus-shaped circular hotspots

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scattered across the diagram, each of which provides additional information when clicked. These hotspots correspond to important parts of the reactor system, such as the reactor pressure vessel, control rods, coolant fluid pump, and other components essential to the nuclear fission process.

Hotspot 1: Control Rods

Control rods made of materials such as boron or cadmium are inserted into the reactor to control the chain reaction. The rods absorb some of the neutrons released during fission, reducing the chain reaction and providing control.

Hotspot 2: Shielding

Shielding protects workers and the environment from radiation. The reactor vessel and fuel rods are enclosed in a thick layer of concrete and steel to absorb radiation and prevent it from escaping into the environment.

Hotspot 3: Moderator

The moderator is made of graphite (or water). It slows down the neutrons released during fission, making the neutrons more likely to be absorbed by the uranium nuclei, and keeping the chain reaction going. Without the moderator, the reactor would need to use much more enriched uranium to maintain a chain reaction.

Hotspot 4: Fuel Rods

The enriched uranium is contained in long cylinders called fuel rods.

Hotspot 5: Heat Exchanger

The heat exchanger transfers heat generated by the nuclear reaction to water, which produces steam that turns the turbines. The water used in the heat exchanger is kept separate from the water used to cool the reactor to prevent radioactive materials from escaping into the environment.

This interactive provides a comprehensive yet concise overview of a nuclear reactor's components and their functions. It is a useful tool for understanding how a nuclear reactor works, the role of each component, and how they interact to maintain a controlled nuclear fission reaction.

We can see from **Interactive 1**, that fuel rods are placed in a reactor vessel filled with a liquid, which acts as a coolant. The graphite moderator slows down the neutrons released by the fission reactions, allowing the neutrons to be more easily absorbed by other U-235 nuclei, triggering a chain reaction.

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It is important to control the rate of the chain reaction to prevent overheating and possible meltdown. Control rods are inserted into the reactor vessel to absorb some of the neutrons and slow down or stop the chain reaction as needed. The control rods can be raised or lowered to adjust the amount of neutron absorption and maintain a safe reactor temperature.

As the fuel rods undergo fission, they release heat energy, which is absorbed by the coolant water. This heated water then passes through a heat exchanger, where it transfers its energy to a secondary water system, creating steam. This steam drives turbines, which generate electricity.

After the steam passes through the turbines, it is condensed back into liquid water. This is done by a condenser, which uses a separate water system to cool and condense the steam.

The fission reaction generates a significant amount of gamma rays. Shielding is needed to contain this radiation to protect workers and the environment. Thick layers of concrete and steel are used to create a protective shield around the reactor and other parts of the power plant.

Making connections

Gamma rays are much more penetrating compared to alpha particles and beta particles (subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/)). Thick concrete is needed to absorb the intensity of gamma rays.

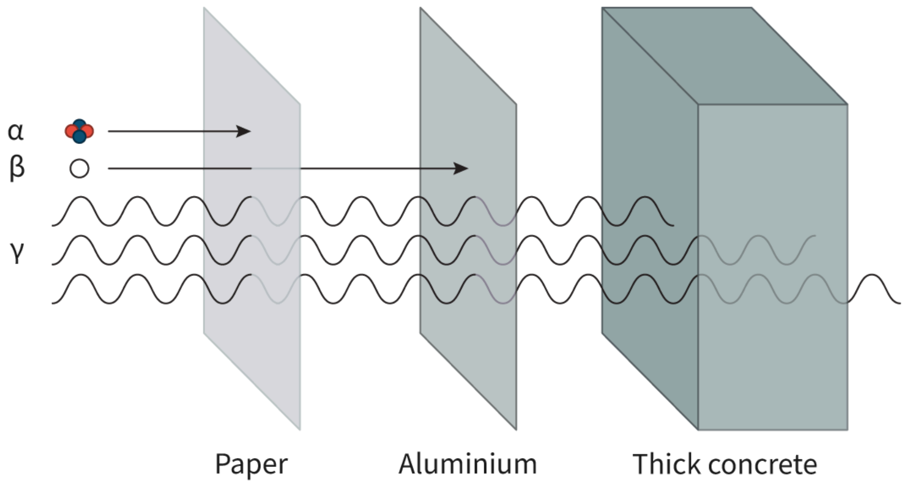

Figure 1. Penetrating power of different types of radiation.

More information for figure 1

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The diagram illustrates the penetrating power of different types of radiation: alpha (α), beta (β), and gamma (γ) rays through various materials. Starting from the left, it shows alpha particles represented by a symbol, followed by an arrow indicating direction, stopped by a thin paper barrier. Beta particles are shown next, with an arrow demonstrating they can penetrate paper but are stopped by an aluminum sheet. Gamma rays, depicted as wavy lines, pass through both paper and aluminum and are only stopped by a thick block of concrete on the far right. The diagram highlights the relative penetrating abilities of these types of radiation, emphasizing the need for thicker shielding against potent gamma rays.

[Generated by AI]

Products of nuclear fission

The products of nuclear fission include highly radioactive isotopes (subtopic E.3 (/study/app/physics/sid-423-cid-762593/book/the-big-picture-id-44319/)), such as cesium-137, strontium-90, and iodine-131. These isotopes emit ionising radiation, which can be harmful to human health and the environment.

The nuclear power industry separates these radioactive materials into two categories based on their radioactivity levels. Low-level waste (LLW) includes clothing, tools and filters that have been contaminated with radioactive material, but only emit low levels of radiation. These items can often be disposed of safely in specific landfills with proper labelling and documentation.

Figure 2 shows how low-level waste is handled.

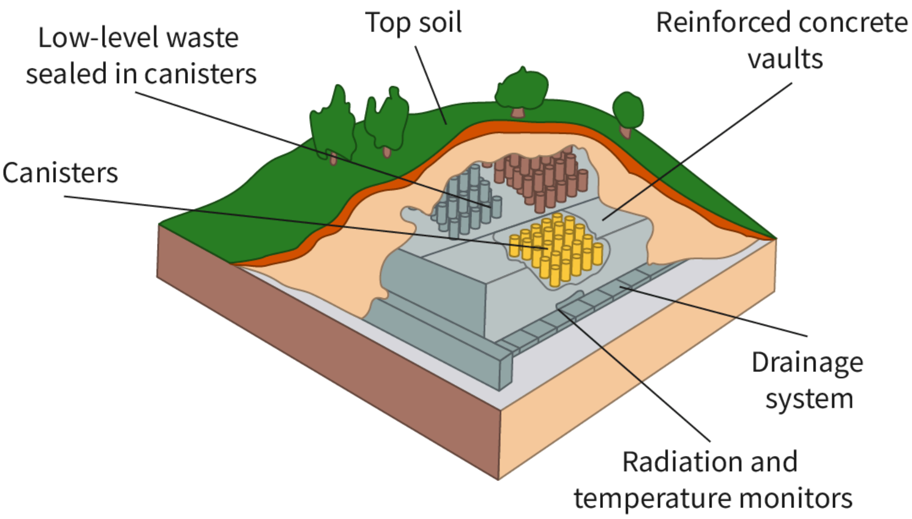

Figure 2. Landfill system for storing low-level waste.

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More information for figure 2

The image is a diagram illustrating a landfill system for storing low-level waste. It shows a cross-sectional view of the ground with various labeled components. At the surface, there is topsoil and some green vegetation. Below the surface, the diagram reveals reinforced concrete vaults containing canisters of low-level waste. The canisters are sealed, and different sections of canisters are shown in distinct colors. The diagram also labels a drainage system and radiation and temperature monitors, indicating the system's infrastructure to handle waste safely. This setup is designed to ensure containment and prevent leakage of radioactive material into the environment.

[Generated by AI]

High-level waste (HLW) includes spent nuclear fuel rods and other highly radioactive materials. These materials emit high levels of radiation and must be stored in special facilities designed to prevent release of radioactivity to the environment. Currently, the most common method of managing HLW is through long-term storage in deep geological repositories. However, it is challenging to find suitable sites due to various factors. What do you think the factors are?

A suitable site should:

- have low seismic activity to minimise the risk of earthquakes
- have low groundwater flow to minimise the interaction between groundwater and the waste packages
- have sufficient depth to provide isolation from the surface environment and human activities
- have a minimal impact on the surrounding environment, such as the ecosystem
- be accessible for monitoring and transportation.

Watch **Video 2** to see how fuel can be extracted from spent fuel rods.

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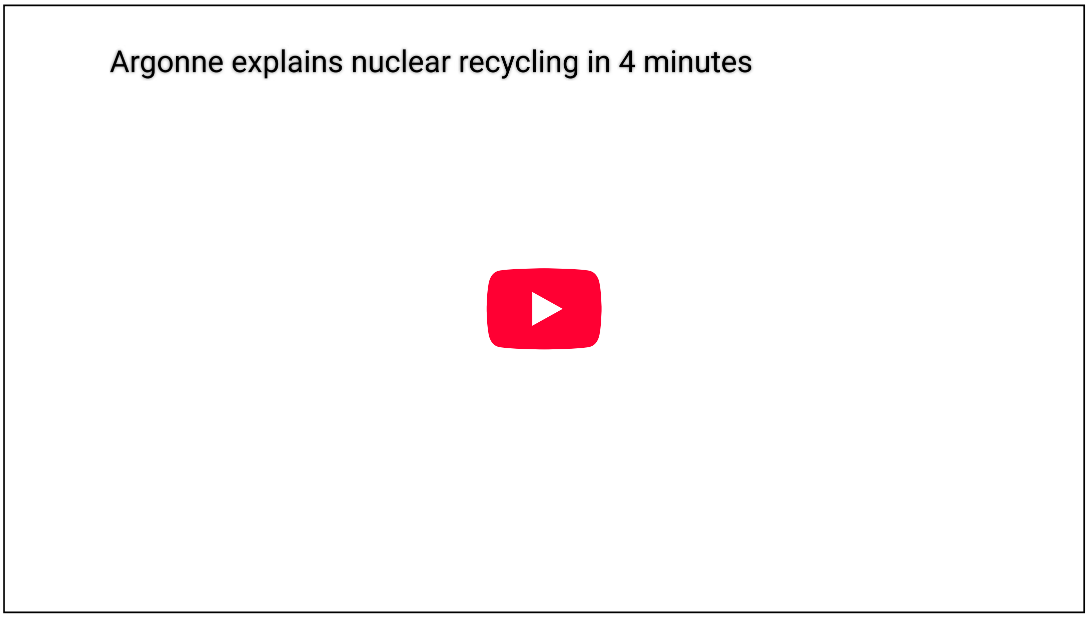

Video 2. Reprocessing nuclear waste.

Work through the activity to check your understanding of nuclear power plants.

Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:** Communication skills — Applying interpretive techniques to different forms of media
- **Time required to complete activity:** 20 minutes
- **Activity type:** Group activity

Look at **Video 3**, which is about strategies for preventing accidents and minimising risks associated with nuclear reactors.

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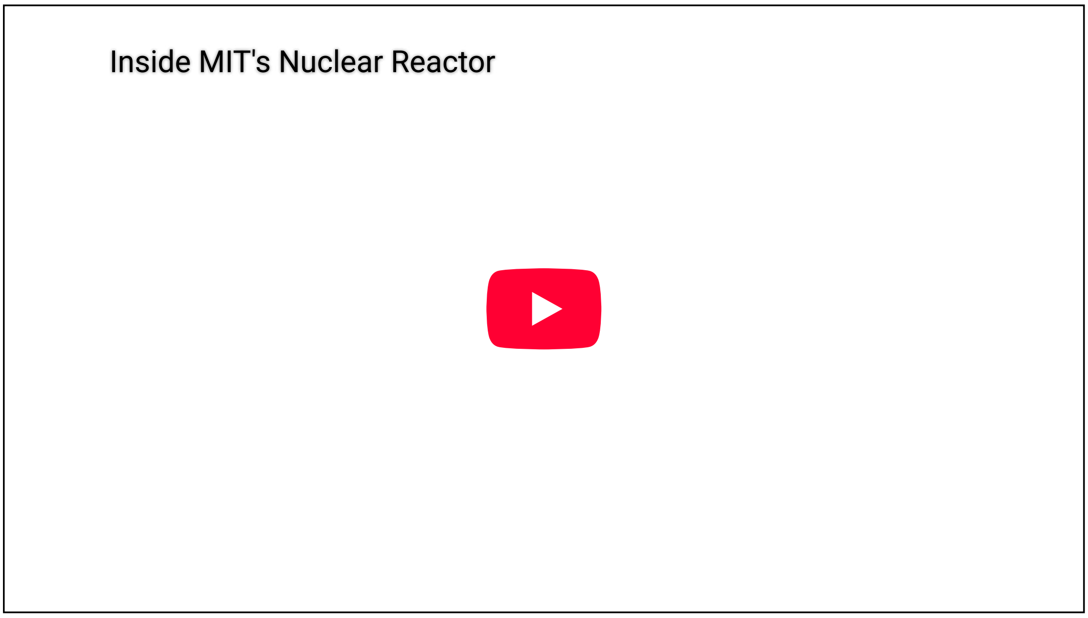

Video 3. Inside a research reactor.

What are the safety measures and protocols in the MIT nuclear reactor lab?

- There is a door to ensure the lab is airtight. Any air leaving is monitored to detect any radioactivity before it is released. The door minimises leakage to the outside air and contamination of the campus.
- There is a background radiation monitor in the lab to keep the staff informed about radiation levels.
- There is 5.5 feet (1.7 metres) of concrete shielding around the reactor, with metal, sand and water for absorbing radiation from the core.
- There is 10 feet (3.0 metres) of water above the reactor core and the top of the reactor.
- Staff wear protective clothing, gloves and shoe covers. They tape their pockets shut so they cannot store objects in them that may accidentally fall from their pockets into the reactor.
- Mechanical arms are used to remotely handle the radioactive substances inside the lead cabinet.
- Any contamination is detected and cleaned off before staff leave the lab.

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Creativity, activity, service

Strand: Service
Learning outcome: Demonstrate engagement with issues of global significance

Look at the information from the World Nuclear Association (https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx) about the latest plans for new nuclear power stations.

Choose a location. Create a presentation for residents of that location to explain how electricity is generated by a nuclear power plant, the potential risks associated with a nuclear power plant, and the safety measures that will be in place.

Work through the activity in the next section (/study/app/physics/sid-423-cid-762593/book/activity-nuclear-reactor-id-47363/) to explore nuclear reactors.

5 section questions

Question 1

SL HL Difficulty:

Identify the row in the table that correctly describes the roles of the moderator and the control rods in a nuclear reactor.

	Moderator	Control rods
A	Cools down the reactor	Absorb neutrons
B	Cools down the reactor	Transfer thermal energy
C	Slows down neutrons	Absorb neutrons
D	Slows down neutrons	Transfer thermal energy

1 C ✓

2 A

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3 B

4 D

Explanation

The moderator slows down the neutrons released during fission. The control rods absorb some of the neutrons to slow down or stop the chain reaction as needed.

Question 2

SL HL Difficulty:

If a nuclear reactor did not have a moderator, what would happen?

1 Very little heat energy would be produced. ✓

2 Too much heat energy would be produced.

3 The nuclear reactor would suffer a core meltdown.

4 Heat energy would not be transferred to water to produce steam.

Explanation

A moderator slows down the neutrons released during fission, making the neutrons more likely to be absorbed by uranium nuclei and sustaining the chain reaction.

Without a moderator, the neutrons released during fission would move too quickly to be absorbed by uranium nuclei. This would reduce the likelihood of further fission reactions, resulting in very little heat energy being produced.

Question 3

SL HL Difficulty:

Which of the following statements are correct about nuclear power plants?

1. They should be built away from residential areas.
2. The reaction chamber should be surrounded by thick concrete walls.
3. They should be built near the ocean for easy disposal of radioactive wastes.
4. They can produce electricity 24 hours a day.

1 1, 2 and 4 ✓

2 1, 3 and 4

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3 2, 3 and 4

4 1, 2 and 3

Explanation

All nuclear power stations are built with thick concrete shields to contain the radiation. They can produce electricity continuously. They tend to be built away from residential areas. Nuclear power plants require water for cooling so tend to be built near large bodies of water. However, they do not dispose of their radioactive wastes in the ocean. Radioactive waste poses a serious threat to the environment and human health. The disposal of such waste is highly regulated and carefully managed.

Question 4

SL HL Difficulty:

Determine which of the following are appropriate ways of handling radioactive substances in the research nuclear reactor.

1. The substances should be shielded in lead or concrete containers.
2. We should wear gloves when picking up the substances with our hands.
3. Radioactive wastes should be labelled clearly and collected separately. Surfaces, equipment, and tools that have come into contact with radioactive materials should be decontaminated regularly.
4. It is important to maintain a safe distance when handling radioactive substances, using a mechanical or robotic arm.

1 1, 3 and 4 ✓

2 2, 3 and 4

3 1, 2 and 4

4 1, 2 and 3

Explanation

Radioactive substances in nuclear power reactors can easily penetrate gloves. Therefore, you would never pick them up with your hands. Mechanical or robotic arms are used to move their positions. All the other statements are correct safety procedures.

Question 5

SL HL Difficulty:

The energy transformation of energy within a nuclear fission power plant can be described in this sequence:

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1. The 1 nuclear pote... ✓ energy from the U-235 nuclei.
2. The 2 kinetic ✓ energy of the fission products (daughter nuclei and neutrons) released from the fission reaction.
3. The 3 thermal ✓ energy used to heat the water into steam.
4. The 4 kinetic ✓ energy in the turbine.
5. The 5 electrical pot... ✓ energy in the transmission cable.

Choose these words for your answer. Some words can be used more than once:

kinetic thermal electrical potential nuclear potential

Accepted answers and explanation

#1 nuclear potential
nuclear

#2 kinetic
thermal

#3 thermal
heat

#4 kinetic
mechanical

#5 electrical potential
electrical

General explanation

In a nuclear fission power plant, the energy transformation begins with the process of nuclear fission. A heavy isotope of uranium contains a large amount of nuclear potential energy. A neutron is absorbed by the U-235 nucleus to form an unstable U-236 atom. The nucleus of U-236 splits into two smaller daughter nuclei and neutrons. This process releases a large amount of energy in the form of kinetic energy, which is transferred rapidly as heat. The heat generated by the nuclear fission reaction is used to boil water, which produces steam. The steam then drives turbines, which are connected to generators that produce electricity. Finally, the electricity is distributed through a power grid to homes and businesses.

E. Nuclear and quantum physics / E.4 Fission

Student view

Activity: Nuclear reactor

Interactive 1. Nuclear reactor simulation.

Activity

Look at the simulation in **Interactive 1.**

Work through the activity to explore nuclear reactors.

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Asking questions and framing hypotheses based upon sensible scientific rationale
- **Time required to complete activity:** 10 minutes
- **Activity type:** Pair activity

1. Select the ‘Nuclear Reactor’ tab.
2. Click the 'Fire Neutrons' red button. What happens when a neutron collides with an U-235 nucleus? What happens when a neutron hits a control rod?

When a neutron collides with an U-235 nucleus, fission occurs, which releases more neutrons for a chain reaction. If a neutron hits a control rod, it ‘disappears’ in the simulation.

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3. Click ‘Reset Nuclei’. Use the handle on the ‘Control Rod Adjuster’ to pull the control rods fully out of the reactor. Click ‘Fire Neutrons’. What happens?
4. Compare the level of chain reaction that occurs when the control rods are inserted deep into the reactor with when they are pulled out of the reactor.

When the control rods are mostly pulled out of the reactor, they absorb fewer neutrons. The chain reaction continues through the U-235 nuclei. This increases the power output of the reactor and the temperature inside the reactor.

When the control rods are inserted deep into the reactor, they absorb many neutrons. This slows down or stops the chain reaction, decreasing the power output of the reactor.

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/nuclear-power-plants-id-46450/print/) Assign

5. Why are control rods used in nuclear reactors?

Without control rods, there is an increase in the probability that the chain reaction could become uncontrollable, leading to excessive energy being released and the temperature of the reactor to become too high. This could lead to a meltdown or explosion. The control rods are used to adjust the rate of nuclear fission in the reactor, ensuring that it stays at a safe rate.

E. Nuclear and quantum physics / E.4 Fission

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/summary-and-key-terms-id-46451/print/) Assign

- Nuclear fission is the splitting of a larger nucleus into smaller nuclei.
- Energy is released during nuclear fission, which can be determined using the equation:

$$E = \Delta mc^2$$

- A nuclear fission chain reaction occurs when the neutrons released during fission are absorbed by other nuclei, which undergo fission and release more neutrons, and so on.
- Nuclear fission can be neutron-induced or spontaneous. A large, unstable nucleus can spontaneously undergo fission without absorbing a neutron.

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- A nuclear power plant has a nuclear reactor which has control rods, a moderator, heat exchangers, and shielding.
- The products of nuclear fission are radioactive isotopes that emit harmful ionising radiation and energy, which is used to produce electricity.
- The waste products of nuclear fission require careful management, and they are disposed of in different ways depending on their category (low-level waste or high-level waste).

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. is the splitting of a nucleus into nuclei.
2. In fission a nucleus absorbs a slow-moving neutron, becomes unstable and then the nucleus splits.
3. The process in which a heavy nucleus splits into two almost equal smaller nuclei without absorbing a neutron is called fission.
4. In a , neutrons released by fission are absorbed by other nuclei, which undergo fission, which releases more neutrons.
5. absorb neutrons, which controls the rate of fission in a nuclear reactor.
6. A moderator is used to slow down , making them more likely to be absorbed by nuclei and cause fission.
7. The system used in nuclear reactors to transfer thermal energy from one fluid to another is known as a .
8. is used to absorb radiation in order to protect people and the environment from its harmful effects.

Nuclear fission | heat exchanger | chain reaction | Control rods | smaller | Shielding | spontaneous | neutron-induced | neutrons

Check

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Interactive 1. Review these key terms: Nuclear Fission.

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Checklist

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/checklist-id-46452/print/) Assign

What you should know

After studying this subtopic, you should be able to:

- Describe that energy is released in spontaneous and neutron-induced fission.
- Determine the energy released in fission reactions.
- Explain chain reactions and their role in nuclear fission reactions.
- Explain the role of control rods, moderators, heat exchangers and shielding in a nuclear power plant.
- Describe the properties of the products of nuclear fission and their management.

E. Nuclear and quantum physics / E.4 Fission

Investigation

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/investigation-id-46453/print/) Assign

- **IB learner profile attribute:**
  - Knowledgeable
  - Communicator
- **Approaches to learning:**
  - Communication skills – Delivering constructive criticism appropriately
  - Social skills – Actively seeking and considering the perspective of others
  - Research skills – Evaluating information sources for accuracy, bias, credibility and relevance

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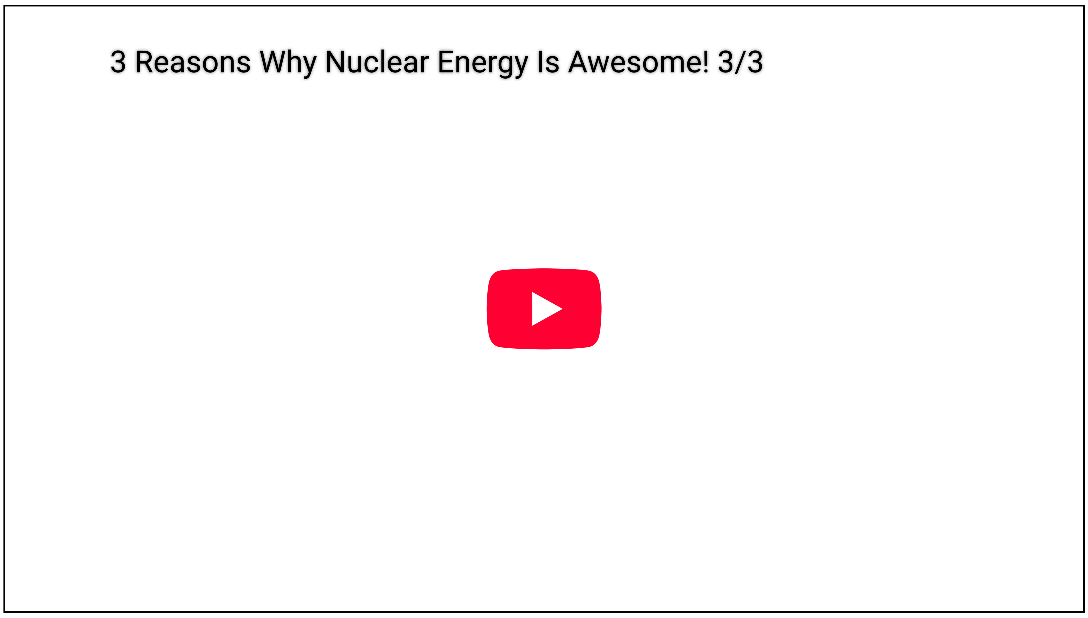
- **Time required to complete activity:** 1 hour
- **Activity type:** Group activity

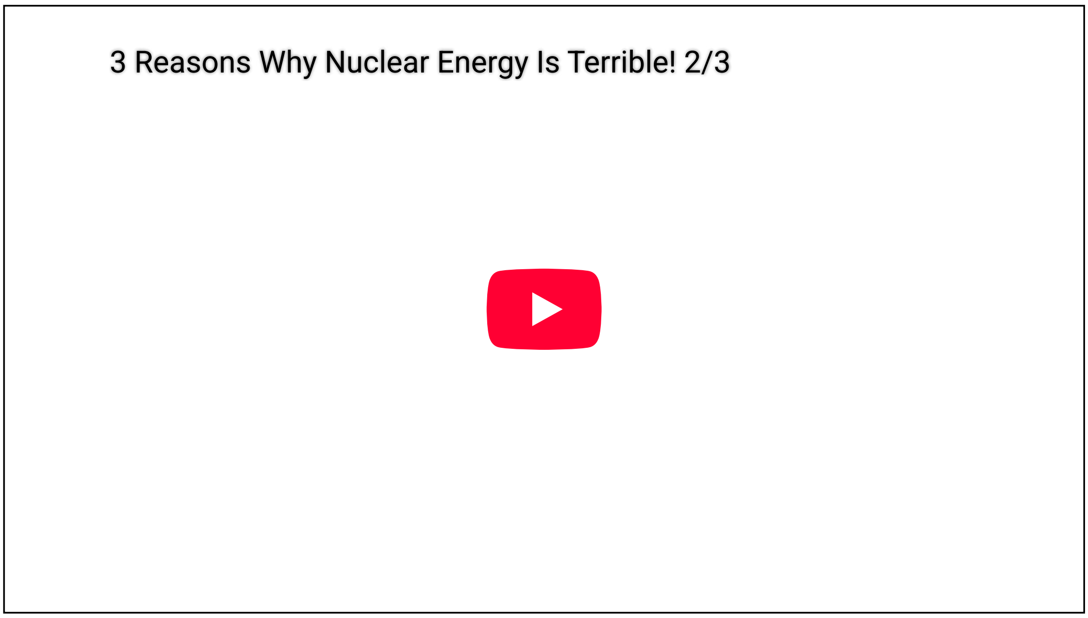
Using nuclear power plants to produce electricity has many benefits. However, a disaster at a nuclear power plant may have deadly and long-term consequences for humans and the environment.

Your task

Watch **Videos 1** and **2** to explore the benefits and the risks of nuclear power.



Video 1. The benefits of nuclear power.



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Video 2. The risks of nuclear power.

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Imagine that there has been a proposal to build a nuclear power plant in your area. Make a list of the benefits and risks, taking into account the following:

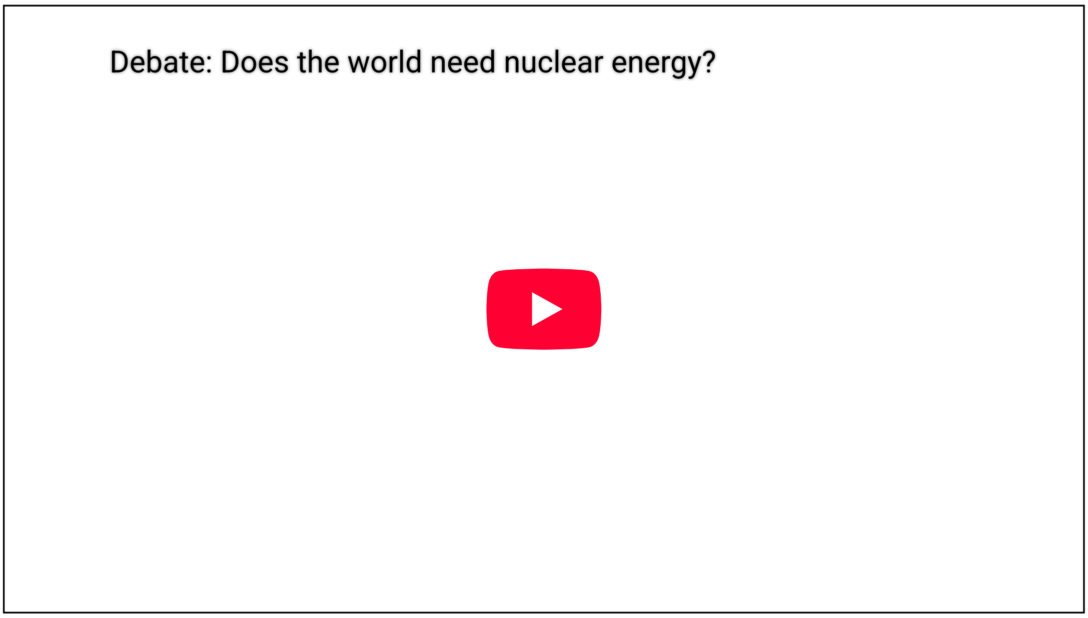
- Where could the nuclear power plant be built and how will that affect local people and the environment?
- How is electricity being produced at the moment in your area – are there fossil fuel power plants or is there renewable energy?
- What will be the effect on the economy of your area – will there be job opportunities?
- How will the nuclear fuel and nuclear waste be managed?
- What would happen if there was a disaster at the power plant?

Decide whether your group is for or against building a nuclear power plant in your area and create a presentation. Present your arguments for or against building a nuclear power plant to the rest of the class. Hold a whole class vote on whether a nuclear power plant should be built in your area.

Nature of Science

Aspect: Science as a shared endeavour

Video 3 shows a debate between environmentalist Stewart Brand and civil and environmental engineer Mark Z. Jacobson in 2011 about nuclear power plants and whether there should be an increase or decrease in their use for the production of electricity.



Video 3. Debating the future of nuclear power.

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The debate was in 2011 with some data from 2006 or before. Renewable energy is becoming cheaper. Are their arguments still valid today? In which ways does the debate represent science as a shared endeavour, in terms of the exchange of ideas and the use of scientific evidence to support positions?

E. Nuclear and quantum physics / E.4 Fission

Reflection

Section Student... (0/0) Feedback Print (/study/app/physics/sid-423-cid-762593/book/reflection-id-47889/print/) Assign

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-46447/).

- In which form is energy stored within the nucleus of the atom?
- How can the energy released from the nucleus be harnessed?
- How can the risks of nuclear power plants be balanced against the benefits?

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:

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- 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

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