Episode 527: Nuclear transmutation

Students need to move beyond the idea that nuclear changes are represented solely by alpha, beta and gamma decay. There are other decay processes, and there are other events that occur when a nucleus absorbs a particle and becomes unstable.

Summary

Discussion: Transmutation of elements. (15 minutes)

Student questions: Balancing equations. (30 minutes)

Discussion: Induced fission. (10 minutes)

Demonstration: The nucleus as a liquid drop. (10 minutes)

Discussion: Fission products and radioactive waste. (10 minutes)

Worked example: A fission reaction. (10 minutes)

Discussion and demonstrations: Controlled chain reactions. (15 minutes)

Discussion: The possibility of fission. (10 minutes)

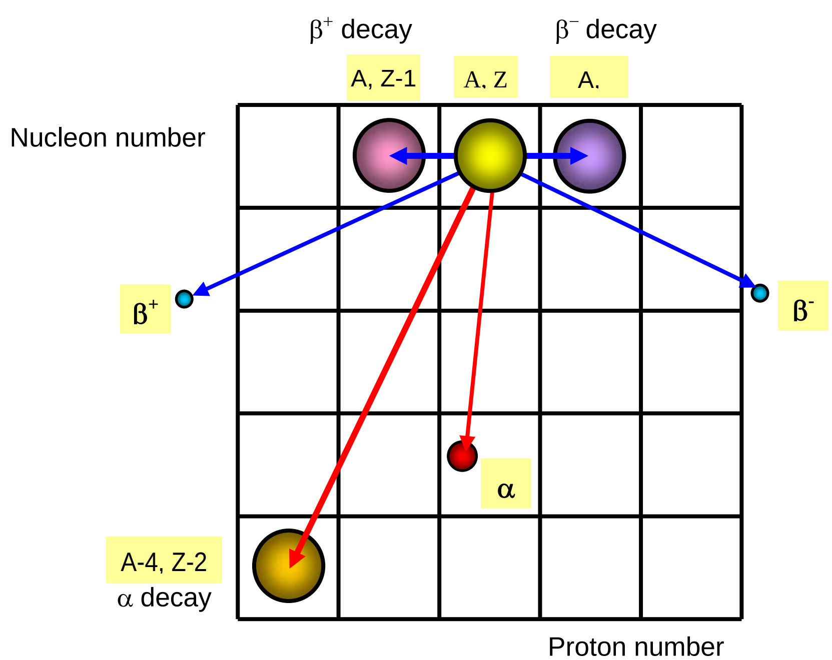
Student questions: Fission calculations. (20 minutes)

Discussion:

Transmutation of elements

Start by rehearsing some assumed knowledge. What is the nucleus made of? (Protons and neutrons, collectively know as nucleons.) What two natural processes change one element into another? (α and β decay). This is transmutation.

Using a Periodic Table, explain that α decay moves two places down the periodic table. What about β^- decay? (Moves one place up the periodic table.) Introduce the idea of β^+ decay. (Moves one place down the periodic table.)



Write general equations for these processes.

There is another way in which an element may be transmuted; for example, the production of radioactive ^{14}C used in radio-carbon dating in the atmosphere by the neutrons in cosmic rays.

$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$

The first *artificial* transmutation was achieved by Rutherford by bombarding nitrogen with α particles. (This experiment was also important in demonstrating that protons are found inside nuclei.) Ask your students to complete the following nuclear equation that summarizes Rutherford's transmutation of nitrogen into oxygen:

$He + ^{14}_{7}N \rightarrow O + ^{1}_{1}H$

They should get $^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H$

Cockroft and Walton were the first to 'split' the atom, by bombarding lithium with protons from their accelerator.

$^{1}_{1}H + ^{7}_{3}Li \rightarrow ^{8}_{4}Be \rightarrow 2\,^{4}_{2}He$

Student questions:

Balancing equations

Students can practise balancing equations.

TAP 527-1: Isotope production

Discussion:

Induced fission

In the examples above, small parts are 'chipped off' nuclei. The behaviour of the heaviest natural element, uranium, is different. It breaks up into two large chunks – into two elements nearer to the middle of the periodic table – so-called *induced fission*. The two lighter elements are referred to as *fission fragments*.

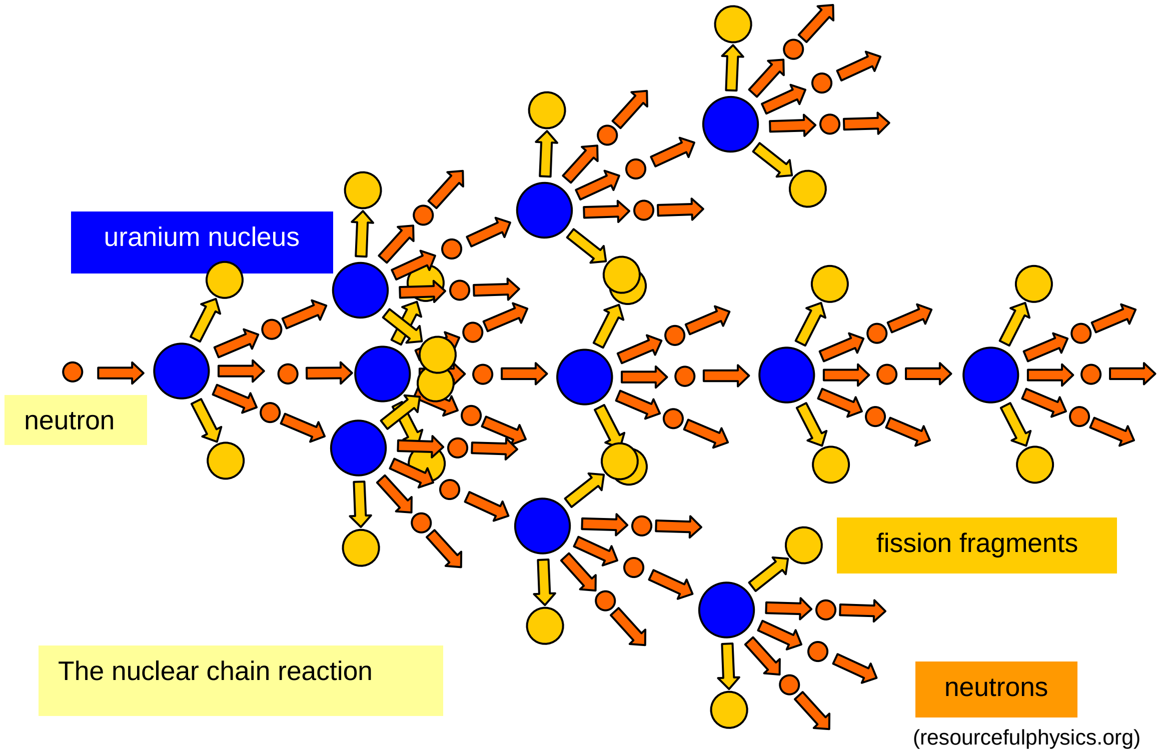
How do the two common isotopes of uranium $^{235}_{92}U$ and $^{238}_{92}U$ differ? ($^{238}_{92}U$ has three more neutrons than $^{235}_{92}U$.) It is the $^{235}_{92}U$ not the $^{238}_{92}U$ that fissions. It absorbs a neutron, then splits into fission fragments, i.e. any two smaller nuclei that can be made from the 235 nucleons of the $^{235}_{92}U$.

TAP 527-2: Nuclear fission

Demonstration:

The nucleus as a liquid drop

In many ways, nuclei behave like a drop of liquid. Show a water filled balloon - a good model for a nucleus. After the absorption of the neutron, the nucleus of $^{238}_{92}U$ wobbles. As soon as the electric charge distribution departs from the spherical (pinch the balloon into a dumbbell like shape) the



mutual coulomb repulsion between the two ends drives the fission process. An alternative is to grease a plate and put a large drop of water on it. Wobble the plate about and watch the drop split.

Discussion:

Fission products and radioactive waste

Most of the energy released is in the form of the kinetic energy of the fission fragments. Because they have a relatively high fraction of neutrons, they are unstable, and decay with short half-lives. They form the 'high-level' radioactive waste that cannot be simply disposed of; it has to be stored somewhere for a minimum of 20 half lives.

By what factor will the activity fall after 20 half lives? ($1/2^{20}$ is about 10^{-6}, or one-millionth)

^{137}Cs has a half life of 30.23 years: 20 half lives = 605 years

^{90}Sr has a half life of 28.1 years: 20 half lives = 562 years

Think about the consequences if waste disposal has to be engineered to remain intact for many centuries. (Which engineering structures have existed for the last 600 years?)

Worked example:

A fission reaction

Here is the nuclear equation for a typical fission process:

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{138}_{53}I + {}^{95}_{39}Y + ?$$

What is required to balance the equation? (3 neutrons)

Why are there some neutrons left over? (Relate this to the *N* - *Z* curve. The heaviest elements have the largest neutron excess to remain stable. The two lighter fission fragments have a higher fractional neutron excess; hence some are 'left over'.) These 'left over' neutrons are the vital key to unlock nuclear power using fission.

Discussion + demonstrations:

Controlled chain reactions

If at least one surplus neutron can induce fission in another ^{235}U nucleus and so on, then a self sustaining release of nuclear energy is possible. For a power station a *controlled* chain reaction is needed. Should each fission result in *more* than one further fission, then the chain reaction is said to diverge. In a bomb the aim is to get the chain reaction to diverge as fast as possible.

Blow up two balloons; let one fly off; release the other slowly, to illustrate the difference between uncontrolled and controlled energy release.

There are a number of analogues of chain reactions that can be demonstrated at this point, using matches or lines of dominoes.

TAP 527-3: Chain reactions

TAP 527-4: Fission analogues

Discussion:

The possibility of fission

What are the chances that a neutron will strike another nucleus? First recall that atoms are mostly empty space. The nuclei of two adjacent uranium atoms are typically 10,000 nuclear diameters apart. Emphasise this by picking a pupil in the middle of the class, and estimating her/his width (0.3 m?). Where will the next 'pupil nuclei' be situated? (3 km away.) A fast-moving neutron will travel a long way before it strikes another nucleus.

In fact, most neutrons are absorbed by ^{238}U nuclei, which are much more common than ^{235}U, and quite good at absorbing fast neutrons. Instead of fissioning they transmute into ^{239}Pu which is fissile, the favourite explosive material for making nuclear bombs. Pure natural uranium is incapable of sustaining a fission reaction – *less* than one fission neutron succeeds in inducing a further fission.

Ask your students how this problem might be overcome in order to have a controlled chain reaction. (The answer is the introduction to the next episode.)

Student questions:

Fission calculations

Calculations of energy released in fission events.

TAP 527-5: Fission – practice questions

TAP 527-1: Isotope production

The production of radio-nuclides by nuclear transmutation is now big business. They are for use in medicine (diagnostic and therapy) and industry (imaging, tracers, process monitoring etc) and are made by neutron bombardment in nuclear reactors and by proton, deuteron ($^{2}_{1}H$) or α particle bombardment by accelerators.

Complete these equations that represent examples of these processes.

$$^{31}_{15}P + ? \rightarrow {}^{32}_{15}P + ? + \gamma$$

$$^{2}_{1}H + {}^{17}_{7}N \rightarrow {}^{15}_{8}O + ?$$

$$^{4}_{2}He + {}^{16}_{8}O \rightarrow {}^{18}_{9}F + ? + ?$$

$$^{4}_{2}He + {}^{121}_{51}Sb \rightarrow ? + {}^{1}_{0}n$$

Find out the half-lives of the isotopes produced in these processes

Find out a typical use of these products.

Practical advice

These questions are to help your students write decay equations and carry out research.

Half lives can be found at
http://www.kayelaby.npl.co.uk/atomic_and_nuclear_physics/4_6/4_6_1.html

Answers

Isotope	Half Life	Emitted particle(s)	Energy / Mev
${}^{32}_{15}P$	14.3 days	beta	1.178
${}^{15}_{8}O$	126 seconds	positron	1.7
${}^{18}_{9}F$	112 minutes	positron	0.6
${}^{123}_{53}I$	13.2 hours	gamma	0.159

$${}^{31}_{15}P \rightarrow {}^{32}_{15}P + {}^{1}_{0}n + \gamma$$

Phosphorus-32 is commonly the highest energy radionuclide encountered in a research setting, and thus requires special caution. Exposure should be avoided and handling should be limited as much as possible.

http://www.unh.edu/ehs/P-32.htm

A solution of phosphate, containing radioactive phosphorus-32, is injected into the root system of a plant. Since phosphorus-32 behaves identically to that of phosphorus-31, the more common and non-radioactive form of the element, it is used by the plant in the same way. A Geiger counter is then used to detect the movement of the radioactive phosphorus-32 throughout the plant. This information helps scientists understand the detailed mechanism of how plants utilized phosphorus to grow and reproduce.

http://www.chem.duke.edu/~jds/cruise_chem/nuclear/agriculture.html

$${}^{2}_{1}H + {}^{17}_{7}N \rightarrow {}^{15}_{8}O + {}^{1}_{0}n$$

Air tagged with O^{15} has been applied to the study in dogs for (*a*) the kinetics of the transfer of oxygen from pulmonary gases to blood, (*b*) the rate of incorporation of oxygen into water during metabolism, *c*) the rate of exchange of plasma water with tissue water

http://ajplegacy.physiology.org/cgi/content/abstract/201/3/582

$${}^{4}_{2}He + {}^{16}_{8}O \rightarrow {}^{18}_{9}F + {}^{1}_{1}H + {}^{1}_{0}n$$

F-18 is for many reasons a useful radioisotope for bio-medical studies. Physically, the longer half-life (112 min) allows more time for relatively complex synthetic manipulations and for biological studies. In addition, the lowest positron energy, and thus its shortest positron range, allows for the sharpest imaging with a high-resolution PET.

http://www.csulb.edu/~cwallis/482/petscan/pet_lab.html

$^{4}_{2}He + ^{121}_{51}Sb \rightarrow ^{123}_{53}I + 2^{1}_{0}n$

The usefulness of iodine-123 whole-body scans in evaluating thyroid cancer

http://tech.snmjournals.org/cgi/content/short/27/4/279

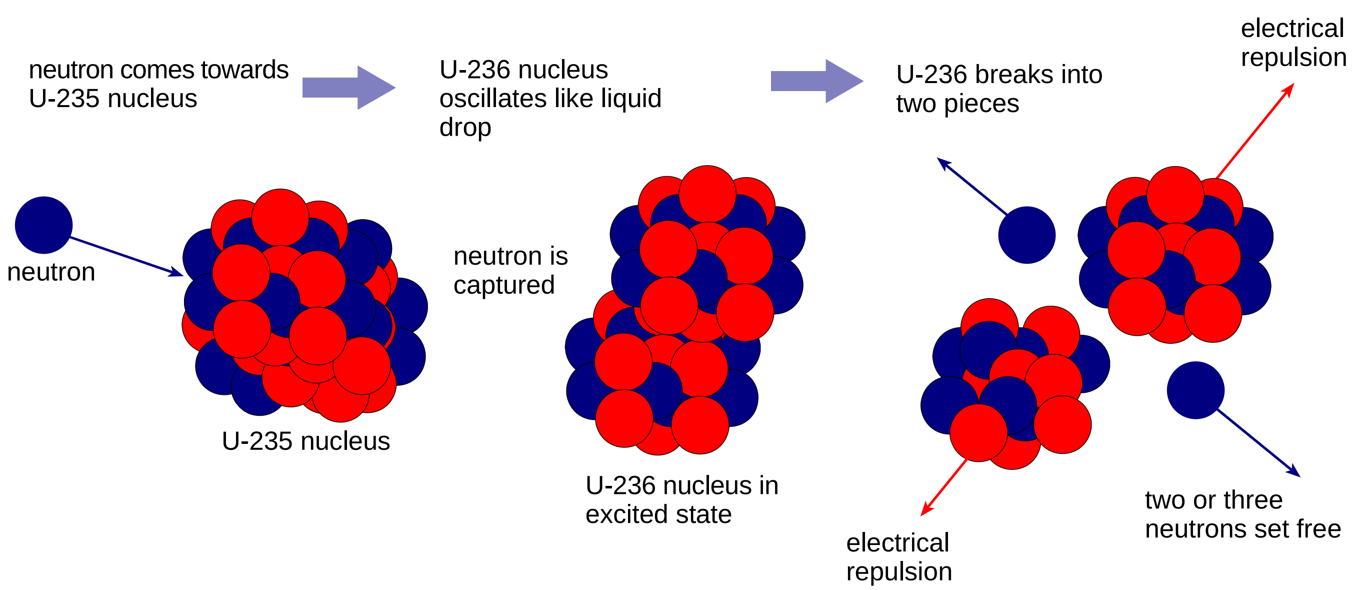
Clinical Pharmacology: Sodium Iodide is readily absorbed from the upper gastrointestinal tract. Following absorption, the iodide is distributed primarily within the extracellular fluid of the body. It is concentrated and organically bound by the thyroid and concentrated by the stomach, choroid plexus, and salivary glands. It is also promptly excreted by the kidneys. The normal range of urinary excretion in 24 hours is reported to be 37-75% of the administered dose varying with thyroid and renal function. The iodide-concentrating mechanism of the thyroid, variously termed the iodide “trap” or “pump” accounts for an iodide concentration some 25 times that of the plasma level, but may increase to as much as 500 times under certain conditions.

http://www.nuclearonline.org/PI/Nycomed%20I-123%20Na%20I%20capsules.pdf

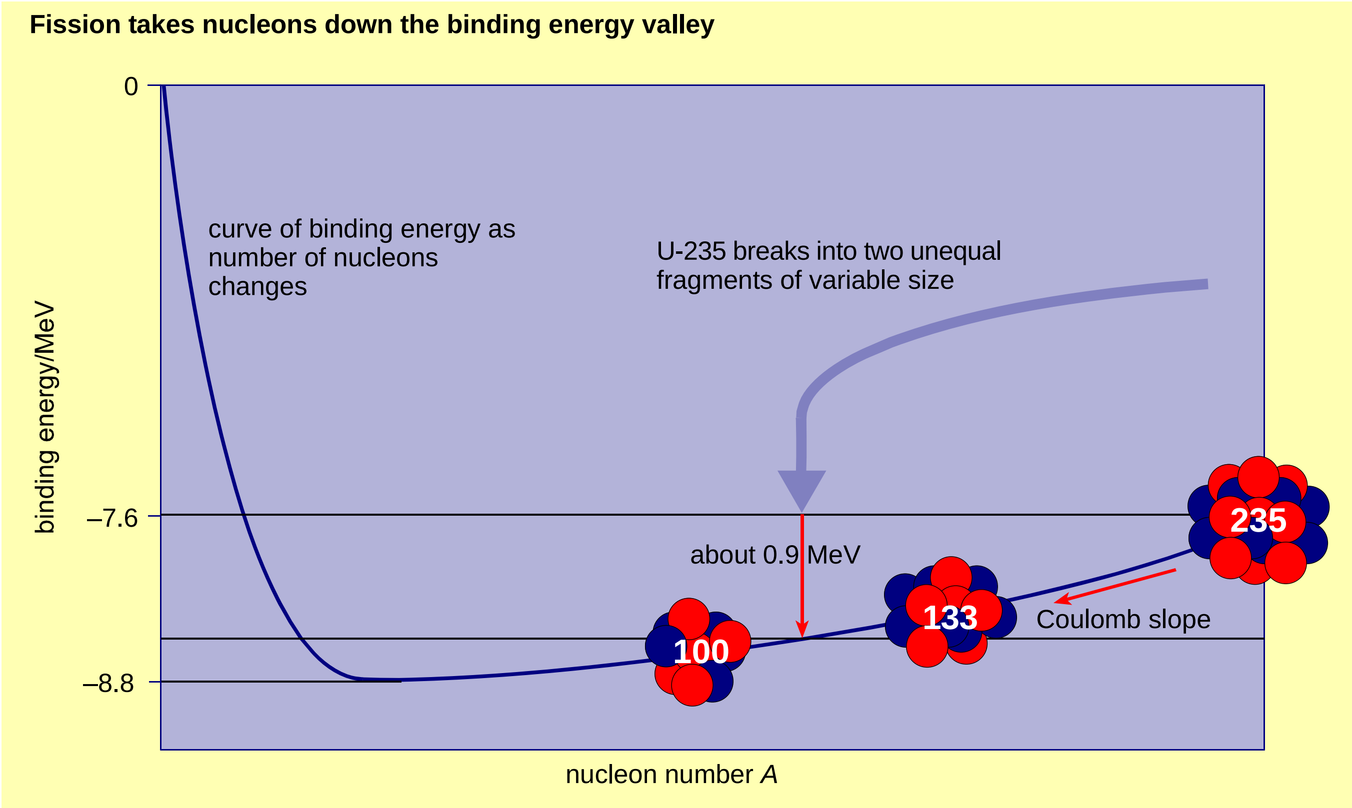
TAP 527- 2: Nuclear fission

This sequence shows how to calculate the energy changes as fission occurs.

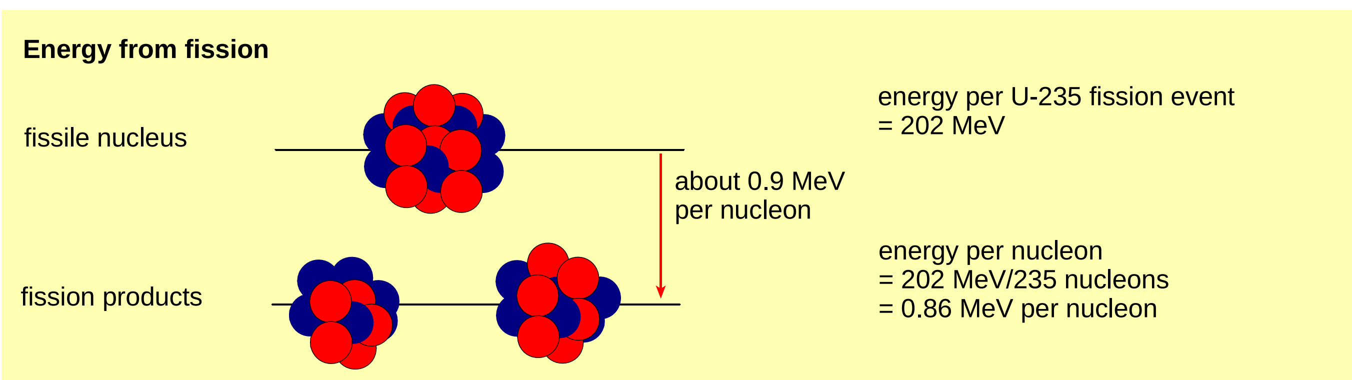
Nuclear fission of uranium-235



Nuclear fission of uranium-235



Nuclear fission of uranium-235



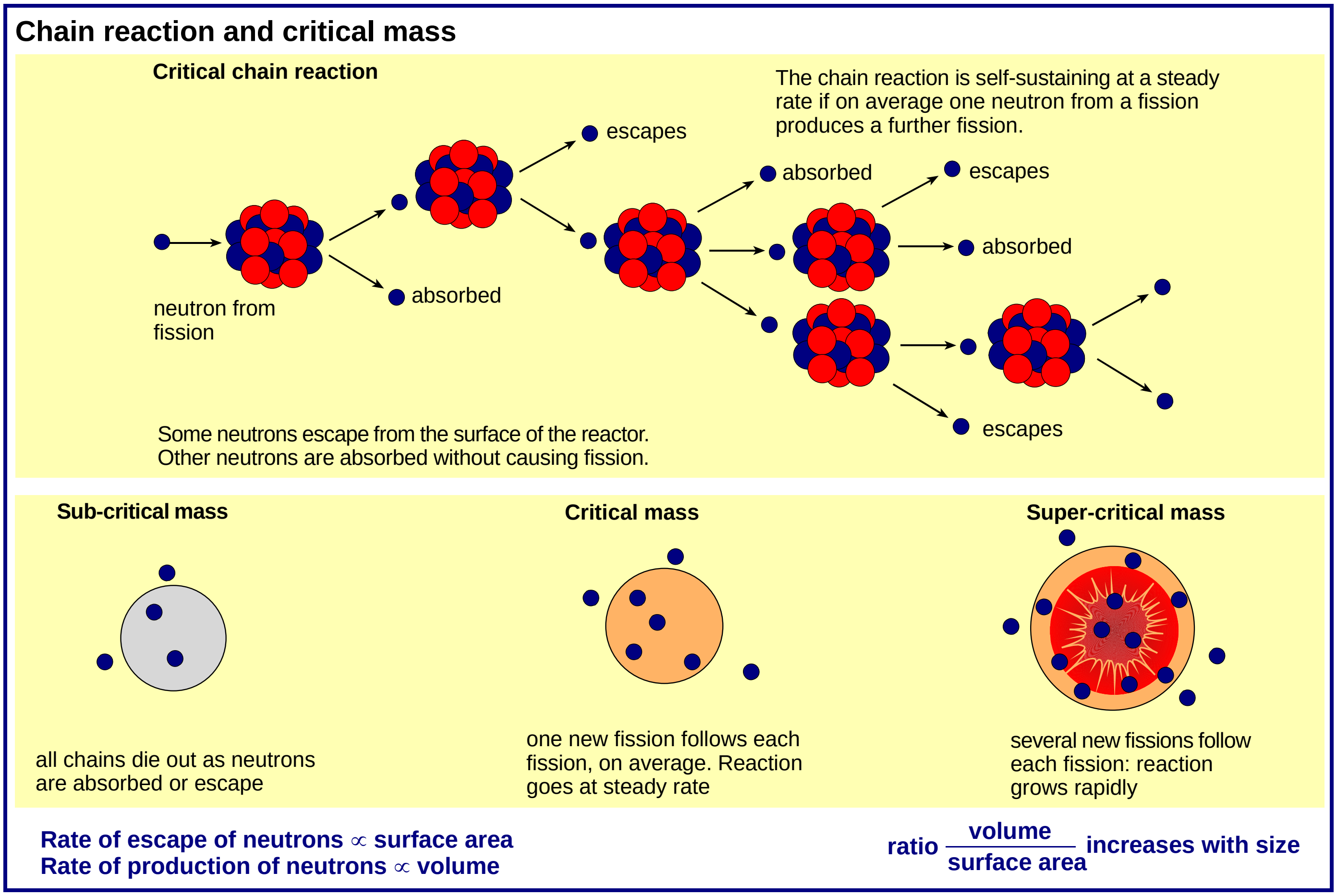
Practical advice

These diagrams are reproduced here so that you can use them for discussion with your class.

External reference

This activity is taken from Advancing Physics chapter 18, 110O

TAP 527- 3: Chain reactions



Practical advice

These diagrams are reproduced here so that you can use them for discussion with your class.

External reference

This activity is taken from Advancing Physics chapter 18, 120O

TAP 527- 4: Fission analogues

1. Controlled energy release

Air filled balloons can be used to show the difference between the controlled release of energy and an uncontrolled explosion, to mimic the controlled chain reaction or the diverging chain reaction (used in a nuclear bomb).

Inflate two balloons and tie the necks. On one stick a piece of sellotape about 5 cm long. When holding the balloon by the neck, have the sellotape facing upwards. Take a good-sized pin (a ray tracing optics pin is ideal). Burst one balloon with the pin – the uncontrolled energy release.

To ham up the demo, now claim that by pushing the pin very carefully into the balloon it is possible not to burst the balloon and thus achieve a controlled energy release. Slowly push the pin into the sellotaped portion of the balloon. Stop when the pin is still sticking out of the balloon. Then remove the pin slowly. Keep checking during the rest of the lesson to monitor the slow deflation of the balloon.

2. Diverging chain reaction

Set up dominoes on edge in the form of a triangle, so that when a domino at the apex is pushed over, it hits two dominoes, they hit 3, which hit 4, and so on.

Alternatively:

Drill a piece of wood with a triangular array of small holes to hold matches, 'live' end upper most. Arrange the spacing so that one lighted match can ignite its neighbours in the next row. Ten rows are ample.

Set the board upright, with the apex of the triangle at the bottom. Light the match at the apex, and see the diverging chain reaction.

!	**Safety assessment!** Try it by yourself first to see what to expect. Have a fire extinguisher handy (it helps to hype up the demo). Beware any heat or smoke alarms that might be activated.

Extinguish by blowing out – ask if anybody in the audience has a birthday today, or close to the actual date, to volunteer.

For a controlled chain reaction: use a simple line of dominoes or matches.

Practical advice

These analogues are provided so you can make a choice of demonstration(s) or activities.

TAP 527- 5: Fission – practice questions

What these are for

These questions will give you some simple practice in handling the ideas and calculations that physicists meet in nuclear fission.

Try these

The process of fission in one type of nuclear reactor proceeds as follows: a nucleus of uranium $^{235}_{92}U$ captures a single neutron. The resulting nucleus is unstable and splits into two or more fragments. These fragments could typically be a pair of nuclei, $^{90}_{36}Kr$ and $^{144}_{56}Ba$ for example. Neutrons are also ejected as a result of the fission. It is these neutrons that go on to cause subsequent fission events and maintain the chain reaction.

1. Write down two balanced equations (the first to the unstable uranium; the second to the final products) that represent this fission process.

2. Calculate the total mass of the original uranium isotope and the neutron. The table gives the atomic masses (in atomic mass units) of the particles found in this question. (1 atomic mass unit (u) ≡ 931 MeV.)

Particle	Mass (u)
$^{1}_{0}n$	1.008 665
$^{90}_{36}Kr$	89.919 528
$^{92}_{36}Kr$	91.926 153
$^{96}_{37}Rb$	95.934 284
$^{138}_{55}Cs$	137.911 011
$^{138}_{56}Ba$	137.905 241
$^{144}_{56}Ba$	143.922 941
$^{235}_{92}U$	235.043 923

3. Calculate the total mass of the four products.

4. Calculate the change in mass. Does this represent energy gained or lost by the system?

5. Convert the mass change into the energy released (in MeV) in the fission event.

6. These particular barium and krypton isotopes are not the only products possible in nuclear fission. Repeat the calculation steps 1–5 with the following possible products caesium-138 and rubidium-96.

Hints

1. There are two equations, the first for the absorption of the neutron; the second for the splitting of the unstable nucleus formed in the absorption. Write down all the original nucleons on the left-hand side of the first equation (do not forget the original neutron). Put all the products on the right-hand side. Check that all protons, neutrons and electrons balance. Energy is also an output of the reaction, call it Q.
2. Add the atomic mass unit values for the uranium and the neutron together.
3. Add the atomic mass unit values for the barium, krypton and two neutrons together.
5. Use $\Delta E = \Delta mc^2$ to carry out this conversion. $c^2 = 9 \times 10^{16}$ J kg^{-1}.

Practical advice

This question set provides repetitive practice in handling nuclear mass changes and conversions between mass and energy. It is suitable for students meeting these ideas for the first time. There is an energy release / nucleon perspective here – a useful teaching point when students have completed this task

Answers and worked solutions

1. $^{235}_{92}\text{U} + {}^{1}_{0}\text{n} = {}^{236}_{92}\text{U} = {}^{90}_{36}\text{Kr} + {}^{144}_{56}\text{Ba} + 2{}^{1}_{0}\text{n} + Q$

2. m = 235.043923 u – 1.008665 u = 236.052 588 u

3. m = 89.919528 u + 143.922941 u + 1.008665 u + 1.008665 u =235.859 799 u

4. Δm =236.052 588 u – 235.859799 u = 0.192 789 u; energy lost

5. ΔE = 0.192 789 u × 931.3 MeV u^{-1} =179.49 MeV

6. m = 137.905241 u + 95.934284 u + 1.008665 u + 1.008665 u =235.856855 u

   Δm = 236.052 588 u – 235.856855 u = 0.195733 u

   ΔE = 0.195733 u × 931.3 MeV u^{-1} = 182.2 MeV

External reference

This activity is taken from Advancing Physics chapter 18, 250S