Episode 527: Nuclear transmutation

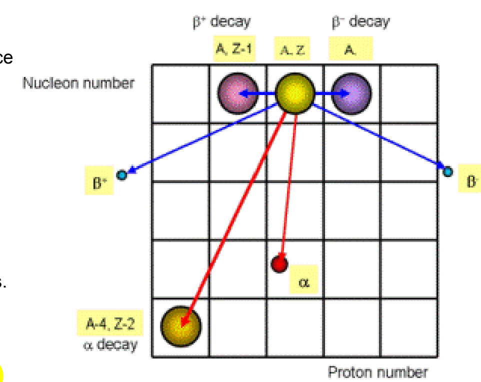
Students need to move beyond the idea that nuclear changes are represented solely by alpha, beta and gamma decay. There are other decay processes, and there are other events that occur when a nucleus absorbs a particle and becomes unstable.

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? (a and b decay). This is transmutation.

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

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

Rutherford discovered the process and later its nature was fully elucidated by Patrick Blackett. (This experiment was also important in demonstrating that protons are found inside nuclei.) Ask your students to complete the following nuclear equation that summarises 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.

Episode 527-1: Isotope production (Word, 50 KB)

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

$^{235}_{92}U$

.

Episode 527-2: Nuclear fission (Word, 123 KB)

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

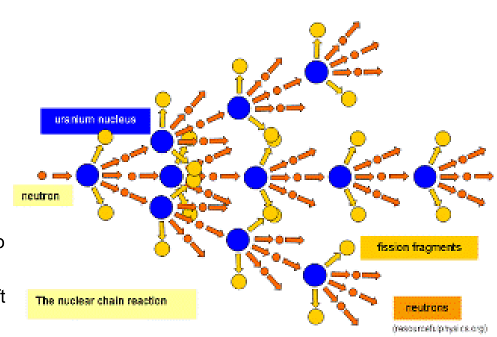
Think about the consequences if waste disposal has to be engineered to remain intact for many centuries. (Which engineering structures have existed for the last 600 years?)

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 and 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.

Episode 527-3: Chain reactions (Word, 173 KB)

Episode 527-4: Fission analogues (Word, 26 KB)

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.

Episode 527-5: Fission – practice questions (Word, 36 KB)

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Episode 527: Nuclear transmutation (Word, 420 KB)

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