Ions produced by radiation carry a current

Demonstration

A radioactive source produces radiation that will ionise the air. The conducting air completes a circuit to charge an electroscope. Use the circuit to show the ionising effect of the radiation and present it as a means of detecting ionising radiation.

Apparatus and materials

- Power supply, EHT, 0–5 kV (with internal safety resistor)
- Metal plates with insulating handles, 2
- Gold leaf electroscope
- Hook for electroscope
- Retort stands and bosses, 2
- Connecting leads
- Sealed source of radium, 5 μC (if available) or sealed source of americium-241, 5 μC
- Holder for radioactive source (e.g. forceps)

Technical notes

A webcam or flexicam could be used to project an image of the gold leaf onto a screen. Alternatively, use a bright lamp to cast a shadow of the leaf onto a screen or wall.

The advantage of using an EHT is that it looks like an electric circuit – albeit a strange one. The electroscope plays the part of a very sensitive meter and the air between the plates is a component whose resistance changes.

Take care when using the electroscope not to make it all seem like a sleight of hand – especially when moving leads around.

Radium is a source of alpha, beta and gamma radiation. However, the beta and gamma radiation do not cause enough ionisation of the air to start a spark.

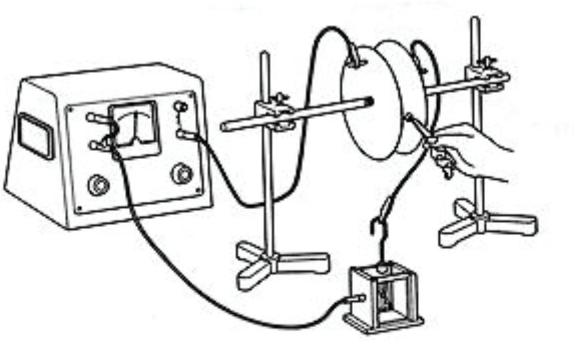
Safety

See guidance note on **Managing radioactive materials in schools**.

A school EHT supply is limited to a maximum current of 5 mA, which is regarded as safe. For use with a spark counter, the 50 MΩ safety resistor can be left in circuit, thus reducing the maximum shock current to less than 0.1 mA.

Although the school EHT supply is safe, shocks can make the demonstrator jump. It is therefore wise to see that there are no bare high-voltage conductors; use female 4 mm connectors, where required.

Read our **health and safety statement**.



Procedure

Setting up
a Fix the two metal plates so that they are parallel to one another and about 1 cm apart.

b Connect one of the plates to the positive terminal of the EHT supply through the safety resistor.

c Connect the other plate to the leaf of the electroscope through the hook.

d Connect the case of the electroscope to the negative terminal of the EHT supply.

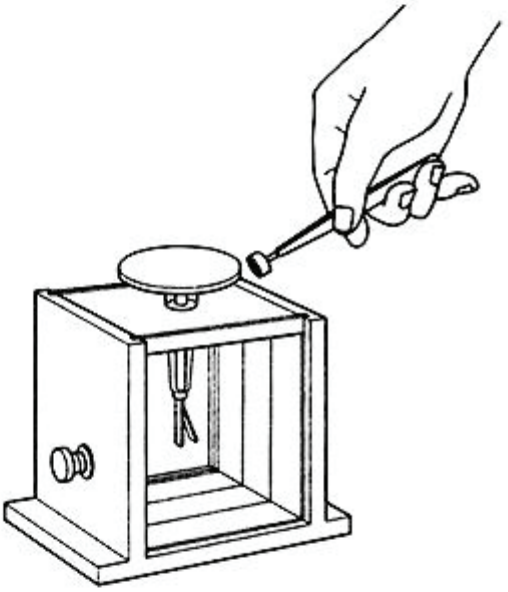
e Connect the negative terminal of the EHT supply to the earth terminal.

Getting a current to flow and charge the electroscope
f Set the EHT supply to about 3 kV and switch it on. The leaf of the electroscope will rise due to induced charges. Reset it by momentarily connecting the leaf to earth.

g Hold the sealed radium source beside the gap and point it between the plates. Watch what happens. The air in the gap is ionised and allows a charge to flow across the gap. This charges the leaf of the electroscope.

h Discharge the electroscope by momentarily connecting the leaf to earth. Try recharging it by holding the source at different angles to, and at different distances from, the plates.

Discharging the electroscope
You can also discharge the electroscope by ionising the air around it.



i Disconnect the electroscope from the supply but keep the base earthed. Replace the disc in the top of the electroscope and charge it using a flying lead from the positive terminal of the power supply (via the safety resistor).

j Point the sealed source over the top of the disc. This will ionise the air and allow the electroscope to discharge.

k Charge the electroscope again and try holding the sealed source at different angles to, and at different distances from, the disc.

The electroscope should discharge quickly to earth when the air above the disc is ionised. If it is discharging too slowly, bring an earthed metal plate up close to the disc of the electroscope.

Teaching notes

1 In the demonstration Ions produced by a flame carry a current (which can be found on the Practical Physics website), students met the idea that ionising the air allows the EHT to charge the electroscope. This demonstration uses the same idea, but now the ionisation is being caused by some invisible radiation coming from the sealed source.

2 As you bring the source towards the gap between the plates, point out that there is no flame and no obvious transfer of energy near the sealed source. Nevertheless, it must be producing ions in the gap, so it must be giving out some invisible radiation.

3 Use the term “ionising radiation” to describe what the source is giving out.

4 The circuit provides a visible means of detecting ionisation in the gap between the two plates. The electroscope provides the visibility, and the high voltage across the air gap is the means of catching ions. This is the same principle as a more convenient detector (the Geiger–Müller tube) and it provides students with a conceptual step towards its construction. This is developed further in **The spark counter.**

This experiment was safety-checked in May 2007

Related guidance notes

- **Managing radioactive materials in schools**
- **Using an electroscope**
- **First models of the atom**

The spark counter

Demonstration

The spark counter is a highly visible (and audible) way of showing and counting ionisation of the air caused by alpha radiation (or a match). It is a useful step towards understanding the Geiger–Müller tube.

Apparatus and materials

- Power supply, EHT, 0–5 kV (with option to bypass safety resistor)
- Spark counter
- Sealed source of radium, 5 μC (if available) or sealed source of americium-241, 5 μC
- Holder for radioactive source (e.g. forceps)
- Connecting leads

Technical notes

The spark counter is a special piece of apparatus (see image above). It consists of a metal gauze with a wire running underneath. Philip Harris calsl it a Spark discharge apparatus.

Any kink or bend in the wire in the counter is liable to cause a spark discharge at that point. If that happens the wire should be replaced. A continuous spark (which will very soon damage the wire) shows that the voltage is too high.

The spark counter should be dust free. Dust around the stretched wire can usually be blown away.

The gauze on top is connected to earth on the EHT supply as a safety precaution.

Radium is a source of alpha, beta and gamma radiation. Beta and gamma radiation do not cause enough ionisation of the air to start a spark.

Safety

See guidance note on **Managing radioactive materials in schools**.

A school EHT supply is limited to a maximum current of 5 mA, which is regarded as safe. For use with a spark counter, the 50 MW safety resistor can be left in circuit, thus reducing the maximum shock current to less than 0.1 mA.

Although the school EHT supply is safe, shocks can make the demonstrator jump. It is therefore wise to see that there are no bare high voltage conductors. Use female 4 mm connectors where required.

Read our **health and safety statement**.

Procedure

Setting up

a Connect the positive, high-voltage terminal of the spark counter to the positive terminal of the EHT supply without the 50 MW safety resistor. (The spark counter's high-voltage terminal is joined to the wire that runs under the gauze.)

b Connect the other terminal on the spark counter to the negative terminal of the power supply and connect this terminal to earth.

c Turn the voltage up slowly until it is just below the point of spontaneous discharge. This is usually at about 4500 V.

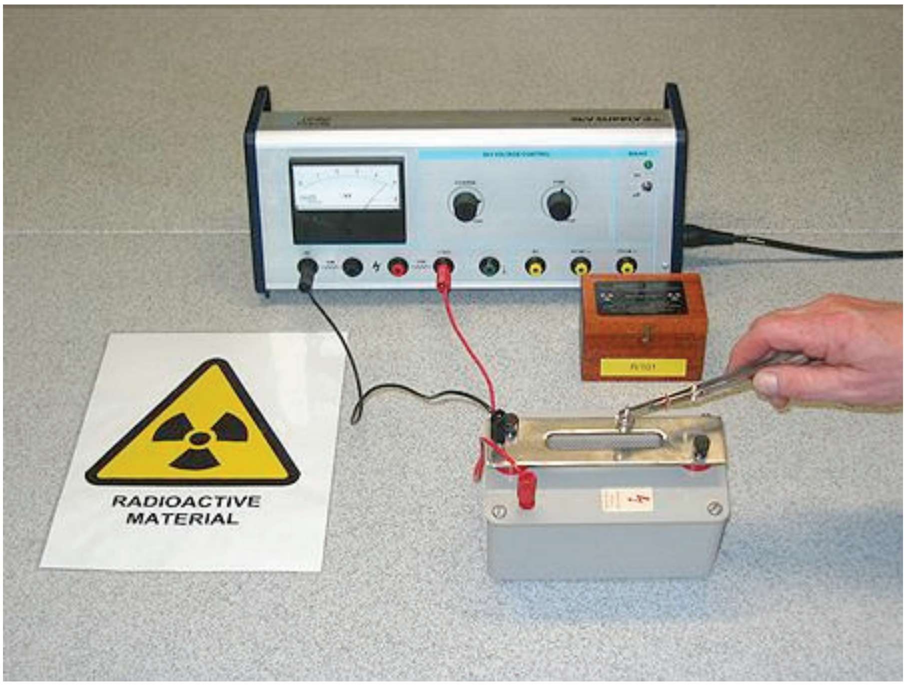


Photo courtesy of Mike Vetterlein.

Carrying out

d Use forceps to hold a radioactive source over the gauze. You should see and hear sparks jumping between the gauze and the high-voltage wire underneath, each time an alpha source is brought near to the counter.

e Move the source slowly away from the gauze and note the distance at which it stops causing sparks.

Teaching notes

1 Draw attention to the random nature of the sparks and hence of the radiation. By counting sparks you are counting the number of alpha particles emitted.

2 You should find that the range of the alpha particles is about 5 cm.

3 You could mention that this is alpha radiation, which is the most ionising of the three main types of radiation.

4 The sparks are similar to those produced by the Van de Graaff. The alpha particles ionise the air, forming positive and negative ions. When these recombine to form neutral atoms, blue light is emitted. The noise of the spark is due to warming the air in the narrow region of the avalanche current, producing a sound wave just like in a lightning strike.

5 A thin sheet of tissue paper or gold foil held between the spark counter and the source will show a reduced range for the alpha particles, or even prevent them from getting to the counter.

6 A version of this apparatus can be seen in the CERN visitor centre (if you happen to be passing). It detects cosmic rays and makes them visible using a 3D array of wire meshes with high voltages between them. The paths of rays can be seen by the trail of sparks that they leave as they ionise the air between the wire meshes. This type of 3D array of high-voltage meshes is the principle used to detect the paths of particles produced in the collision experiments at CERN.

7 Before you use the spark counter showing ionisations from an alpha source, you could use it to count matches (as in Counting matches with an EHT supply, which can be found on the Practical Physics website)

This experiment was safety-tested in June 2007.

Related guidance notes

- **Managing radioactive materials in schools**
- **First models of the atom**

The Geiger–Müller tube

Demonstration

This is a general introduction to the Geiger–Müller (G–M) tube, describing and explaining the basic principles of its operation.

Apparatus and materials

- Scaler
- Holder for G–M tube
- Thin window G–M tube
- Gamma source, as pure as possible (e.g. Co-60 with a filter to stop βη, or Ra-226 with a thick filter)
- Beta source, pure (strontium 90)
- Alpha source, as pure as possible (e.g. Pu-239 or Am-241, which emits γη too)
- Holder for radioactive sources
- Gamma G–M tube if available
- Box of matches

Technical notes

G–M tubes are set up to operate at a voltage within their “plateau”. In self-contained systems, this is set automatically.

The voltage across a G–M tube is generally kept low enough so as not to produce a “roaring” spark when an energetic particle enters it.

G–M tubes are very delicate, especially if they are designed to measure alpha particles. The thin, mica window allows alpha particles to enter the chamber. It needs a protective cover to prevent it from being accidentally damaged by being touched. A good alpha- detecting G–M tube will also count photons. If you light a match in front of it, a few ultraviolet photons will be detected.

Safety

See guidance note on **Managing radioactive materials in schools**.

Read our **health and safety statement**.

Procedure

Setting up

This will depend on the type of G–M tube you are using. If you have a self-contained system, then simply get it ready and switch it on. If you are using an older style G–M tube that plugs into a separate ratemeter or scaler, you will need to set the voltage on the scaler. Do this by following these steps:

a Put a radioactive source in a holder. Fix this in a clamp on a retort stand.

Photograph courtesy of Mike Vetterlein.

b Put the G–M tube in a stand. Adjust it so that it is pointing at the source and is about 5 cm away from it.

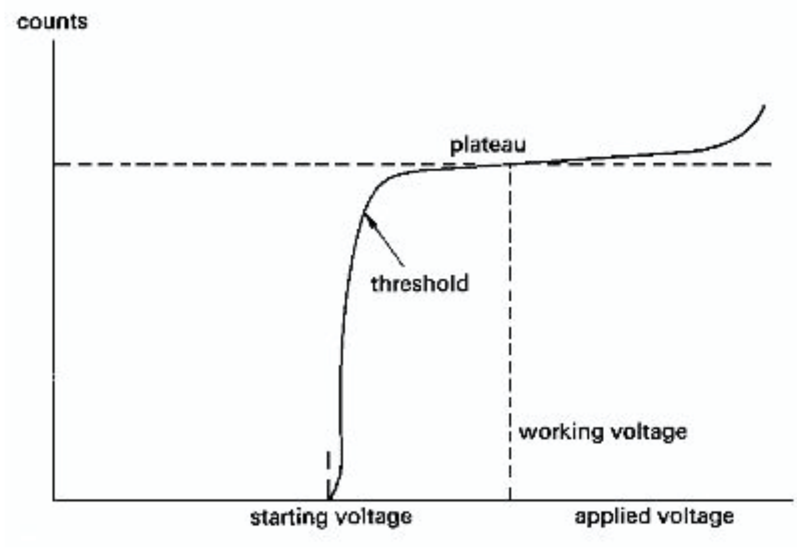
Photograph courtesy of Mike Vetterlein.

c Plug the G–M tube into the scaler (counter) and switch on.

d Start the voltage at about 200 V. Make a note of the number of counts in, say, a 15 s interval.

e Increase the voltage in steps of 25 V.

f You will find that the counts vary with voltage and then reach a plateau. A graph would look like this (you do not need to plot this):



g After the threshold voltage, the count will reach a plateau. It will stay constant over a range of voltages. Set the voltage at a value of between 50 and 100 V above the threshold.

h If the clicking increases when you increase the voltage, you have moved off the plateau. Turn the voltage back down.

i Put the source back in a safe place until you carry out the demonstration.

Carrying out the demonstration

a Switch on the G–M tube counting system.

b Highlight the fact that there is a background count.

c Bring a radioactive source up to the G–M tube and draw attention to the increase in counts.

d You could measure the background count and the count with the source nearby. Do this over a period of 30 s. Draw attention to the difference.

Teaching notes

1 Discuss what is happening in the G–M tube. Point out that it is more sensitive and more stable than the spark counter.

Draw attention to the differences in count between the G–M tube and the spark counter. The G–M tube detects all of the ionisation events that take place inside it. Each one is registered.

Discuss the G–M tube as a development of the spark counter. You could say: “The wire of the spark counter is placed inside a metal shield, which acts as the other electrode, and the high-voltage supply is incorporated into the scaler The scaler does the counting of the pulses of charge delivered by the electron avalanches to the central wire. The tube is filled with a suitable gas mixture to make sure that each spark does not last too long. When the spark is quenched, the tube and the scaler are ready to count a ‘bullet’ from another radioactive atom’s ‘explosion’. As you can see and hear, the tube can react very quickly to each avalanche."

2 The G–M tube works on the same principle as the spark counter: an ionisation between two high-voltage electrodes produces a pulse of current (an avalanche of charge) between the electrodes. The differences are that the G–M tube is sealed, it contains a low-pressure gas (usually argon with a little bromine) and it is usually part of a circuit with a scaler counter.

The scaler counter records and counts each pulse of charge.

The phenomena inside a tube are much more complicated than the simple story of ionisation producing an avalanche of electrons. Inside the tube, ultraviolet photons probably play an important part, as well as colliding electrons and ions, and the detailed picture is extremely complex.

An ionising particle will produce a pulse of charge of almost constant size. The size of the pulse does not vary with the energy or amount of ionisation produced by the ionising particle.

The number of pulses represents the number of ionising particles coming into the tube.

G–M tubes do not distinguish between one kind of particle and another, or between a more energetic particle and a less energetic one, provided that the particle enters the tube and does not pass right through (as most γη do).

This experiment was safety tested in August 2007.

Related guidance notes

- **Sparks in the air**
- **Managing radioactive materials in schools**

Diffusion cloud chamber

Class experiment

The Taylor diffusion cloud chamber is a simple piece of equipment that will clearly show alpha-particle tracks. It is cheap enough to allow students, in groups, the opportunity to do their own experiment. They are fascinated by the tracks and watch them for a long time. This is something to be enjoyed and not hurried.

You can do this as a demonstration. However, students will prefer waiting for their own apparatus to produce results rather than yours. Also, if you have 8–10 groups of students, each with their own cloud chambers, you are more likely to get some results sooner or later.

Apparatus and materials

For each student or group:

Taylor diffusion cloud chambers
Lamp, 12 V, 24 W and power supply (shining through 1 cm wide slit)
Flexicam or webcam linked to a projector (optional)

Available to the class/teacher:
Bottle of ethanol (DMS) and dropper under teacher control
Dry ice or CO_2 cylinder and dry ice attachment (see **Making dry ice**).

Technical notes

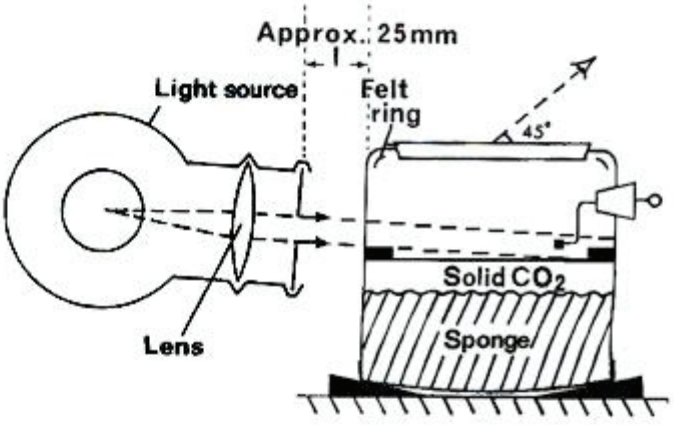
1The cloud chamber works by allowing a supersaturated vapour to build up close to the base of the chamber. The air at the top of the chamber should become saturated with methylated spirits vapour. Any air that sinks to the bottom of the chamber is cooled by the dry ice underneath. This makes the air supersaturated and the vapour will condense if given the opportunity (i.e. one or more condensation nuclei). These are provided by alpha particles from the thoron source.

2 When putting the methylated spirits into the chamber it is essential that none of it falls on the source, otherwise alpha particles may not penetrate it.

3 Surprisingly little dry ice is needed in these chambers. Practice will show you how much is required – usually 2–3 cm^3.

4 The radioactive source is normally a spot of radioactive paint containing thorium or radium.

5 Insert the wire source holder in the cork and place the cork in the hole in the side of the chamber, with the source near the floor. Position the source in the gap between the metal foils by rotating the wire.



6 Place the chamber on the three levelling wedges. Clean the underside of the Perspex lid before replacing.

7 Direct a flat beam of light across the chamber towards the radioactive source. (The foils should be bent back slightly so that they do not reflect light onto the chamber floor.)

8 NB The only make of cloud chamber (diffusion type) that is currently available is from Ideas for Education in Co. Fermanagh, Northern Ireland (tel 028 6863 1209), also supplied by Timstar and Scientific & Chemical Supplies.

Safety

This demonstration uses a weak radioactive source. If any radioactive paint has flaked off the source inside the chamber, do not use it.

Since ethanol is in use there must be no naked flames in the room.

Wear eye protection and gauntlet-style leather gloves when making or handling solid carbon dioxide.

Read our **health and safety statement**.

Procedure

a It is very important that the class has plenty of time for this experiment. Allocate the cloud chambers so that there is one for every three or four students.

b The laboratory will need to blacked out, but the light from the 12 V lamps is enough for everyone to see what they are doing.

c To set up the chambers, put methylated spirits on the padding inside the top of the chamber using a dropper. A drop or two can also be put on the black base of the chamber and allowed to spread over it. Make sure that none gets onto the thoron source.

d Unscrew the base of the whole apparatus and put a little dry ice in contact with the baseplate. Put the foam back to keep the dry ice in contact with the plate. Screw the base cap on again and turn the chamber the right way up.

e It is important that the cloud chamber is level. Place it on the three wedges provided. These can be adjusted to get it level. If it is not level you will see convection currents moving in the chamber and these can be used as guides in levelling.

f The top must be put back on the chamber. Rubbing it with a clean duster will charge it sufficiently to provide an adequate electric field inside the chamber to sweep away old ions.

g Illumination is important. Adjust the 12 V lamps so that there is a layer of illumination a few millimetres above the baseplate.

h Usually within 30 s of setting it up you should see alpha tracks coming from the weak radioactive source, which is inserted in the side of the chamber.

i If the tracks are not sharp, try rubbing the top again to improve the electric field. This cleans out any stray ions in the air.

Teaching notes

1 Tell the class that what they can see is the effect of alpha radiation. They are not seeing the radiation itself but the condensation that has formed on ions left behind by the radiation. By the time the condensation forms, the alpha particle has long gone.

2 Draw attention to the amount of ionisation that each alpha particle produces and to the length of its track.

3 You could also draw attention to the fact that the tracks are straight, showing that nearly all of the collisions are with something much lighter (usually removing an electron from an atom). Forked tracks may be seen when the alpha particle strikes a more massive particle, such as one of the constituents of air.

4 If students watch the cloud chamber for long enough, and the chambers are well balanced, they may see the tracks of high-energy electrons from cosmic rays.

5 Short, thin, spiralling tracks may be seen. These are electrons or β particles in the Earth's magnetic field.

6 A fast group could swing the source behind the thin foil. This will absorb the α particles but let the β particles through. The wavering tracks of the β particles may be seen if conditions are optimum.

7If you start to get some good results, you could use a flexicam to project the live tracks onto a screen or whiteboard. You could even record a short movie for posterity and to refer back to in later lessons. Similarly, if you have access to a digital camera, you could take some still photographs and use them in a wall display or Powerpoint presentation in a follow-up lesson. You could offer a prize for a forked track!

This experiment was safety checked in August 2007.

Related guidance notes

- **How clouds form**
- **Managing radioactive materials in schools**
- **Making dry ice**
- **Alpha-particle tracks**
- **Evidence for the hollow atom**
- **Classroom management in semi-darkness**

Alpha radiation: range and stopping

Demonstration

This focuses on the properties of alpha particles.

Apparatus and materials

- Power supply, EHT, 0–5 kV (with option to bypass safety resistor)
- Spark counter (or Geiger–Müller tube and counter)
- Sealed pure alpha source, plutonium-239 (^{239}Pu), 5 µCi (if available) or sealed (semi-pure) alpha source, americium-241 (^{241}Am), 5 µCi
- Holder for radioactive source (e.g. forceps)
- Connecting leads
- Set of absorbers (e.g. paper, aluminium and lead of varying thickness)
- Cloud chamber photographs of alpha-particle tracks

Technical notes

Note that 5 µCi is equivalent to 185 kBq.

Sealed sources for radium and plutonium are no longer available (see **Radioactive sources – isotopes, radiation and availability** guidance note). However, if you have them in your school, you can use them as long as you follow your school safety policy and local rules (see **Managing radioactive materials in schools**).

If you do not have a pure alpha source (^{239}Pu), you need to be careful about trying to show the properties of alpha using a Geiger–Müller tube. The radiation from a mixed source like ^{241}Am can penetrate aluminium and has a long range. This is because it gives out gamma as well as alpha radiation (see guidance note **Radioactive sources: isotopes, radiation and availability**).

The most effective way of demonstrating the properties of alpha radiation is to use the spark counter. If you do not have a pure alpha source (i.e. you are using radium or americium-241), this is the recommended method because the spark counter does not respond to beta or gamma radiation. See **The spark counter** experiment for technical notes.

The Geiger–Müller tubes are very delicate, especially if they are designed to measure alpha particles. The thin, mica window needs a protective cover so that it isn't accidentally damaged by being touched.

Education suppliers stock a set of absorbers that range from tissue paper to thick lead. This is a useful piece of equipment to have in your prep room. You can make up your own set. This should include tissue paper, plain paper, some thin metal foil (e.g. cigarette paper or the wrapping from a chocolate from an assortment box) and a small piece of gold leaf.

Safety

See guidance note on **Managing radioactive materials in schools**.

A school EHT supply is limited to a maximum current of 5 mA, which is regarded as safe. For use with a spark counter, the 50 MΩ safety resistor can be left in circuit. This reduces the maximum shock current to less than 0.1 mA.

Although the school EHT supply is safe, shocks can make the demonstrator jump. It is therefore wise to see that there are no bare high-voltage conductors. Use female 4 mm connectors where required.

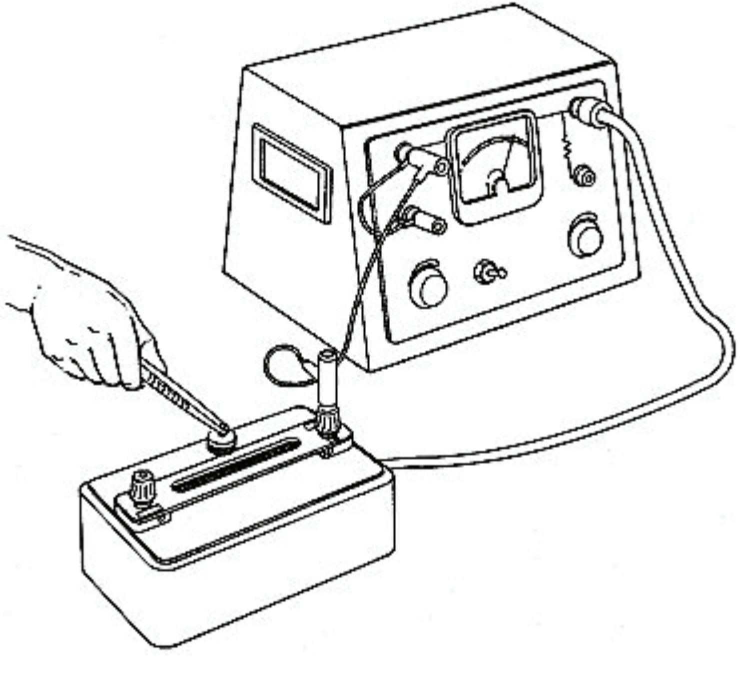
Read our **health and safety statement**.

Procedure

Setting up
a Connect the positive, high-voltage terminal of the spark counter to the positive terminal of the EHT supply without the 50 MΩ safety resistor. (The spark counter's high-voltage terminal is joined to the wire that runs under the gauze.)

b Connect the other terminal on the spark counter to the negative terminal of the power supply and connect this terminal to earth.

c Turn the voltage up slowly until it is just below the point of spontaneous discharge. This is usually between 3000 and 4500 V.



Carrying out the demonstration
d Use forceps to hold a radioactive source over the gauze. You should see and hear sparks jumping between the gauze and the high-voltage wire underneath.

e Move the source slowly away from the gauze and note the distance at which it stops causing sparks.

f Move the source back towards the gauze so that sparks reappear. Try putting a very thin piece of paper between the source and the gauze. Try a thicker piece of paper. Note the effect in each case.

g Taking care that the foil does not blow onto the spark counter, try putting a thin piece of foil between the source and the gauze. With gold leaf or aluminium, you may still get some sparks. Try moving the source (and the gold leaf) away from the spark counter. You should find that the range has been reduced by the gold leaf.

Teaching notes

1 This experiment can be done in conjunction with beta radiation: range, and stopping and Gamma radiation: range and stopping. You might decide to merge these three experiments so that you do the range of all three types of radiation. You can then show the effects of a magnet on beta radiation separately.

2 You should find that the range of the alpha particles is between 3 and 10 cm. The alphas from americium have a range of about 3 cm, from plutonium 5 cm, and the most energetic ones from radium, 7 cm. Refer to the **Diffusion cloud chamber** experiment to reinforce this evidence.

3 You should find that the alpha particles are stopped by anything except the very thinnest of paper or foil leaf. The gold leaf reduces the range of the alpha particles because they lose energy getting through the gold leaf.

4 Remind students that this is alpha radiation, which is the most ionising of the three main ionising radiations. Link this with the observations that you have made. Alpha radiation collides with a lot of particles through which it passes, and ionises them. Because of this it loses its energy quickly and is slowed down and absorbed.

5 Refer to cloud chamber photographs of alpha-particle tracks, showing them being deflected in a magnetic field. The deflection is too small to measure in the school laboratory, but it shows that they have a positive charge. The small deflection shows that they have a relatively large mass. Collisions with helium produce 90° forks showing that they have the same mass as helium (nucleus). You can say that alpha particles are thought to be a doubly ionised helium atom. If the students have already met the idea of nuclei, then you can call alpha particles a helium nucleus.

6 An alpha particle is a helium nucleus with two positively charged protons and two neutral neutrons. The atomic mass of the radiating atom falls by four units when an alpha particle is emitted. The speed of an alpha particle can be as much as 15×10^6 m/s.

7 You can discuss the dangers of radioactivity in general. Radiation harms people by making ions in our flesh and thereby upsetting or killing cells. The more ionising the radiation, the more harmful it is. This makes sources of alpha radiation very hazardous – especially if they are ingested.

8 Relate the hazard to the safety precautions that you are taking during the demonstration.

This experiment was safety checked in August 2006.

Related guidance notes

- **Sparks in the air**
- **Managing radioactive materials in schools**
- **Radioactive sources: isotopes and availability**

Beta radiation: range and stopping

Demonstration

This demonstration focuses on the properties of beta particles.

Apparatus and materials

- Geiger–Müller (G–M) tube
- Holder for G–M tube
- Scaler (if needed by G–M tube)
- Sealed pure beta source, strontium-90 (^{90}Sr), 5 µCi
- Set of absorbers (e.g. paper, aluminium and lead of varying thickness)

Technical notes

Note that 5 µCi is equivalent to 185 kBq.

G–M tubes are very delicate, especially if they are designed to measure alpha particles. The thin, mica window needs a protective cover so that it is not accidentally damaged by being touched.

Some education suppliers now stock all-in-one G–M tubes with a counter (e.g. Science Enhancement Programme).

An all-in-one G–M tube and counter.

Education suppliers stock a set of absorbers that range from tissue paper to thick lead. This is a useful piece of equipment to have in your prep room. You can make up your own set. This should include tissue paper, plain paper, some thin metal foil (e.g. cigarette paper or the wrapping from a chocolate from an assortment box) and a small piece of gold leaf.

To cut off the direct path in step **d**, the lead block from the absorbers kit is just adequate but a block with a bigger area is better.

Safety

See guidance note on **Managing radioactive materials in schools**.

This experiment puts the demonstrator at a small risk of receiving a dose of β radiation. The demonstrator should avoid leaning over the source and, if it cannot be avoided, should reduce the exposure time as far as possible. There are safer versions of doing this experiment that use a collimated beam.

Read our **health and safety statement**.

Procedure

Absorption of beta radiation

a Set up the G–M tube in a clamp and connect it to a scaler if needed.

b Fix the beta source in its holder and clamp it near to the G-M tube.

c Take 30 s counts of the beta particles at equal distances from the G-M tube until the count rate falls to the background count rate.

d A graph of count rate against separation distance could be plotted.

e Move the beta source and G-M tube so that a reasonable count rate is achieved (about 5 cm). Then place paper, cardboard, thin aluminium sheet and lead sheet between the source and the G-M tube.

Teaching notes

1 The absorption properties of beta radiation make it useful in industrial and some medical applications.

2 Experiments that deflect beta particles can measure their speed, which is about 98% of the speed of light. Thus relativistic effects cause an increase in the electrons mass.

This experiment was safety checked in April 2006.

Related guidance notes

- **Managing radioactive materials in schools**
- **Radioactive sources: isotopes and availability**
- **Nature of ionising radiations**

Beta radiation: deflection in a magnetic field

Demonstration

This focuses on the properties of beta particles. You can show that beta radiation is deflected in a magnetic field. This is an impressive and striking demonstration.

Apparatus and materials

- Geiger–Müller (G–M) tube
- Holder for G–M tube
- Scaler (if needed by G–M tube)
- Sealed pure beta source, strontium-90 (^{90}Sr), 5 μCi
- Large magnet (Eclipse major)
- Retort stands, bosses and clamps, at least 3
- G-clamps, 2
- Lead block
- Set of absorbers (e.g. paper, aluminium and lead of varying thickness)

Technical notes

Note that 5μCi is equivalent to 185 kBq.

G–M tubes are very delicate, especially if they are designed to measure alpha particles. The thin, mica window needs a protective cover so that it is not accidentally damaged by being touched.

You need to be especially careful handling the G–M tube near the Eclipse magnet, which is extremely strong. The magnet can pull the G–M tube out of a loose holder or even your fingers. Make sure that the G–M tube is firmly fixed in a retort stand, which is clamped to the bench before you start setting up the magnet.

Some education suppliers now stock all-in-one G–M tubes with a counter (e.g. Science Enhancement Programme).

An all-in-one G–M tube and counter.

Education suppliers stock a set of absorbers that range from tissue paper to thick lead. This is a useful piece of equipment to have in your prep room. You can make up your own set. This should include tissue paper, plain paper, some thin metal foil (e.g. cigarette paper or the wrapping from a chocolate from an assortment box) and a small piece of gold leaf.

To cut off the direct path in step **d**, the lead block from the absorbers kit is just adequate, but a block with a bigger area is better.

Safety

This experiment puts the demonstrator at a small risk of receiving a dose of β radiation. The demonstrator should avoid leaning over the source and, if it cannot be avoided, should reduce the exposure time as far as possible. There are safer versions of doing this experiment that use a collimated beam and much smaller magnets.

Read our **health and safety statement**.

Procedure

a Use a G-clamp to secure one of the retort stands to a bench. Fix the G–M tube in its clamp. Point it up at an angle of about 30°.

b Secure a second retort stand to the bench and clamp the holder for the radioactive source in it. Again, face it up at an angle of about 30°.

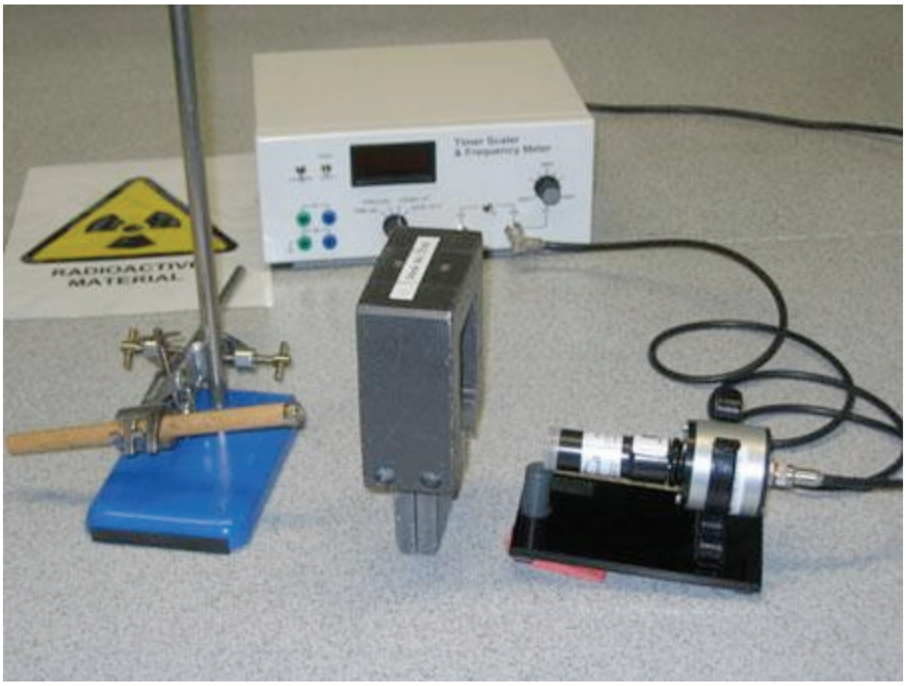


Photo courtesy of Mike Vetterlein.

c Place the large eclipse magnet on the lead block between the source and the G–M tube. Arrange it so that the source and the G–M tube are pointing into the middle of the space between its two poles. Take great care when handling the magnet near the G–M tube – it is very strong and can dislodge the tube if it's not secure.

d Check that you can detect beta particles with the magnet in place (in one orientation). If the magnet is removed or turned round, you will not be able to detect beta particles. Make a note of which orientation works.

e Remove the magnet and return the beta source to the safe.

Carrying out

f Remove the magnet, place the sealed source in its holder and show that the lead sheet blocks all of the radiation. You can slide the lead in and out to show that beta radiation is being emitted and will reach the G–M tube.

g Put the magnet in place (the correct way) and show that the G–M tube is now detecting beta radiation. You can show this by using various shields next to the source and the tube.

h Rotate the poles of the magnet through 180° and show that this prevents the radiation from reaching the G–M tube.

Teaching notes

1 The beta radiation is deflected by the magnetic field. This suggests that it is made of moving charges.

2 With advanced students you may want to use Fleming's left-hand motor rule to identify the sign of the charge as negative.

3 The fact that the beta radiation is deflected by only a finite amount means that it must have mass. This suggests that it is a stream of (negative) particles. Students might suggest that it is made of electrons. You can say that further studies show this to be the case.

4 You might mention that alpha radiation is also deflected by a magnetic field, but not enough to measure with this equipment. It is deflected the other way, showing that it has a positive charge.

5 The absorption properties of beta radiation make it useful in industrial and some medical applications.

6 Experiments that deflect beta particles can measure their speed, which is about 98% of the speed of light. Thus relativistic effects cause an increase in the electrons' mass.

7 Beta particles are formed when a neutron changes into a proton in the nucleus and the atom rises one place in the periodic table.

This experiment was safety checked in August 2007.

Related guidance notes

- **Managing radioactive materials in schools**
- **Radioactive sources: isotopes and availability**
- **Nature of ionising radiations**

Gamma radiation: range and stopping

Demonstration

This focuses on the properties of gamma radiation. You can show that it is much more penetrating than alpha or beta radiation and has a much longer range.

Apparatus and materials

- Geiger–Müller (G–M) tube
- Holder for G–M tube
- Scaler (if needed by G–M tube)
- Sealed "pure" gamma source, cobalt-60 (^{60}Co), 5 μCi or sealed radium source
- Set of absorbers (e.g. paper, aluminium and lead of varying thickness)

Technical notes

Note that 5μCi is equivalent to 185 kBq.

Cobalt-60 is the best gamma source. However, you may have a sealed radium source in your school. This gives out alpha, beta and gamma radiation. You can use it for this experiment by putting a thick aluminium shield in front of it. This will cut out the alpha and beta radiations.

An alternative is to try using a G–M tube sideways. The gamma radiation will pass through the sides of the tube but alpha and beta radiation will not. Some gamma particles interact with the tube wall and knock electrons into the tube gas where they are detected. This effect enhances the detection efficiency of the gamma particles. You can do a quick check by doubling and tripling the distance between the source and the axis of the G–M tube and seeing if the count follows an inverse square law (by dropping to a quarter and a ninth).

Some education suppliers now stock all-in-one G–M tubes with a counter (e.g. Science Enhancement Programme).

An all-in-one G–M tube and counter.

Education suppliers stock a set of absorbers that range from tissue paper to thick lead. This is a useful piece of equipment to have in your prep room. You can make up your own set. This should include tissue paper, plain paper, some thin metal foil (e.g. cigarette paper or the wrapping from a chocolate from an assortment box) and a small piece of gold leaf.

Safety

See guidance note on **Managing radioactive materials in schools**.

Read our **health and safety statement**.

Procedure

a Set up the G–M tube and attach it to the scaler if needed.

b Put the source in its holder and clamp it a few centimetres from the G–M tube.

c Show that the gamma radiation has a long range in air – at least 80 cm. You could show that the count is falling off with distance, and gets smaller and smaller rather than stopping altogether.

d Show that the gamma radiation will penetrate paper, cardboard, aluminium and thin lead, but is greatly reduced by thick lead.

Teaching notes

The moral of this story is that to protect yourself from gamma radiation the best thing to do is to move a long way away.

Discuss the uses of gamma radiation in industry and for medical imaging and treatment. The applications are based on its penetrating power.

Remind students that gamma radiation is much less ionising than alpha.

This experiment was safety tested in August 2007.

Related guidance notes

- **Managing radioactive materials in schools**
- **Radioactive sources: isotopes and availability**
- **Nature of ionising radiations**

Gamma radiation: inverse square law

Demonstration

Gamma radiation is part of the electromagnetic spectrum. It is not absorbed by the air but its intensity decreases because it spreads out. Therefore the intensity varies with the inverse square of distance: it follows an inverse square law. You can show this in the laboratory and use it as evidence to support the fact that gamma radiation is part of the electromagnetic spectrum.

Apparatus and materials

- Geiger–Müller (G–M) tube
- Holder for G–M tube
- Scaler
- Metre rule
- G-clamps, 3
- Sealed "pure" gamma source, cobalt-60 (^{60}Co), 5 µCi or sealed radium source
- Set of absorbers (e.g. paper, aluminium and lead of varying thickness)

Technical notes

Note that 5 µCi is equivalent to 185 kBq.

Cobalt-60 is the best pure gamma source. However, you may have a sealed radium source in your school. This gives out alpha, beta and gamma radiation. You can use it for this experiment by putting a thick aluminium shield in front of it. This will cut out the alpha and beta radiations.

An alternative is to try using a G–M tube sideways. The gamma radiation will pass through the sides of the tube but alpha and beta will not. You can do a quick check by doubling and tripling the distance between the source and the axis of G–M tube and seeing if the count follows an inverse square law (by dropping to a quarter and a ninth).

Using the G–M tube sideways has an added advantage that you have an accurate measure of where the distance is zero. It is along the axis of the tube.

Education suppliers stock a set of absorbers ranging from tissue paper to thick lead. This is a useful piece of equipment to have in your prep room. You can make up your own set. This should include tissue paper, plain paper, some thin metal foil (e.g. cigarette paper or the wrapping from a chocolate from an assortment box) and a small piece of gold leaf.

Safety

See guidance note on **Managing radioactive materials in schools**.

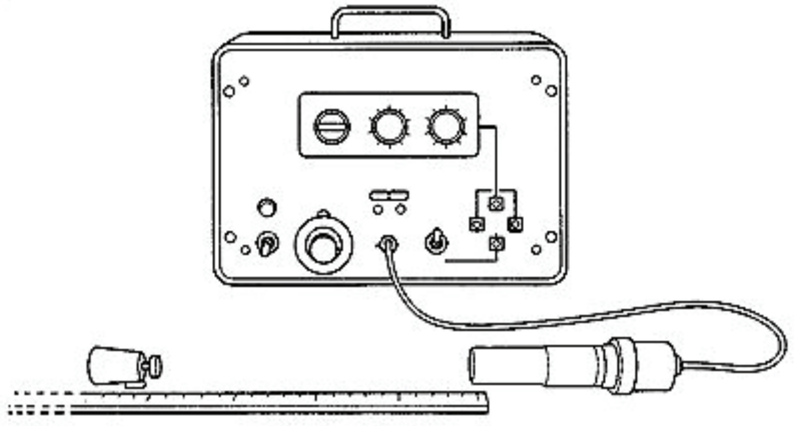
Read our **health and safety statement**.

Procedure

Setting up
a Set up the G–M tube and attach it to the scaler.

b Clamp a metre rule to the bench and line it up with your zero point (in the G–M tube).

c With some G–M tubes, the gamma radiation will pass through the side. Therefore set the G–M tube up at right-angles to the metre rule. The zero point is then the axis of the tube.



d You can check your zero point by doing some quick readings before the lesson. When you double the distance, the count should be a quarter. If it is more than a quarter, then move the tube towards the source to re-zero it. If it is less than a quarter, then your zero point is closer than you reckoned. Move the tube away from the source to re-zero it.

Carrying out
e Measure the background count with the source far away.

f Start with the gamma source 10 cm from the zero point.

g Increase the distance and take measurements of the count rate at 20, 30, 40, 60 and 80 cm.

h Correct the count rates for the background count.

i Plot a graph of corrected count rate against distance. You could use a spreadsheet program to do this.

Teaching notes

1 The shape of the graph shows that the count rate decreases with distance. You can show that it is inverse square by checking that the count rate quarters when the distance doubles (10 to 20 cm; 20 to 40 cm; 30 to 60 cm), falls to a ninth when it trebles (10 to 30 cm; 20 to 60 cm) and drops to a sixteenth when the distance is quadrupled (10 to 40 cm; 20 to 80 cm). (This is only true assuming the source has a small area compared with the cross-section of the detector. Keep the minimum distance large!)

2 A graph of count rate against 1/distance^2 is a straight line.

This is the same law that governs all electromagnetic radiation. This is some evidence that gamma radiation is part of the electromagnetic spectrum.

The moral of this story is that to protect yourself from gamma radiation the best thing to do is to move farther away. At 10 times the distance you will be 100 times as safe.

This experiment was safety tested in May 2006.

Related guidance notes

- **Managing radioactive materials in schools**
- **Radioactive sources: isotopes and availability**
- **Nature of ionising radiations**

Measuring the half-life of protactinium

Demonstration

Measuring the half-life of a radioactive isotope brings some of the wonder of radioactive decay into the school laboratory. Students can witness one element turning into another and hear (or see) the decrease in the radiation that it gives out as it transmutes.

This demonstration uses a “protactinium generator” to show the exponential decay of protactinium-234, a granddaughter of uranium. It has a half-life of just over a minute, which gives students the chance to measure and analyse the decay in a single lesson.

Apparatus and materials

- Holder for Geiger–Müller (G–M) tube
- G–M tube, thin window
- Scaler
- Stopclock
- Retort stand, boss and clamp
- Protactinium generator
- Ratemeter (optional)

Technical notes

Preparation of the protactinium generator

It is now possible to purchase the chemicals already made up in a sealed bottle. One supplier is TAAB Laboratories Equipment Ltd, 3 Minerva House, Calleva Park, Aldermaston, RG7 8NA (tel 0118 9817775), but you can make your own if you prefer.

These quantities make a total volume of 20 cm^3. You can scale them up if you have a larger bottle. (A 30 ml bottle has a capacity of about 35 ml, so there is still room to shake the solution if the total volume is 30 ml.)

1) Dissolve 1 g of uranyl nitrate in 3 cm^3 of water. Wash it into a small separating funnel or beaker with 7 cm^3 of concentrated hydrochloric acid.

2) To this solution, add 10 cm^3 of iso-butyl methyl ketone or amyl acetate.

3) Shake the mixture for about five minutes, then run the liquid into the polypropylene bottle and firmly screw down the cap. It can help to shield the lower half of the bottle with some lead.

4) Place the bottle in a tray lined with absorbent paper.

Once you have made the protactinium generator, you can store it with other radioactive materials, taking care to follow your school code of practice and local rules (see the **Managing radioactive materials in schools** guidance note).

A polypropylene bottle is preferable to polythene because it is somewhat more resistant to attack by the acid and ketone. Nevertheless, polythene bottles can be used, provided that no attempt is made to store the liquid in them for more than a few weeks.

The organic layer that separates out contains the protactinium-234. This decays with a half-life of 68 s.

There is an alternative to protactimium. A new, effective and extremely low hazard system for measuring half-life is available from Cooknell Electronics Ltd, Weymouth, DT4 9TJ. This uses fabric gas mantles designed for camping lights. Each mantle contains a small quantity of radioactive thorium. More details are available on the Cooknell Electronics website.

Safety

See the **Managing radioactive materials in schools** guidance note.

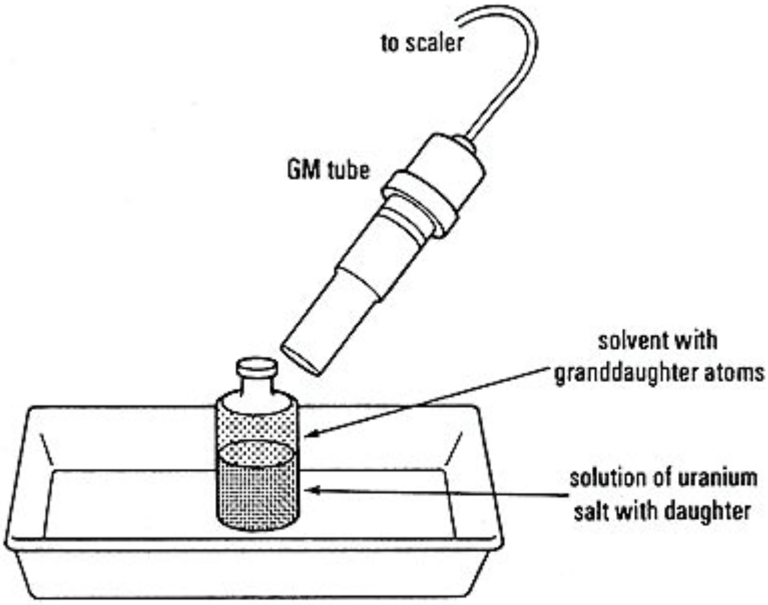
To limit the risk of radioactive liquids being spilt, there should be special instructions in the local rules for handling (and preparing) this source.

Read our **health and safety statement**.

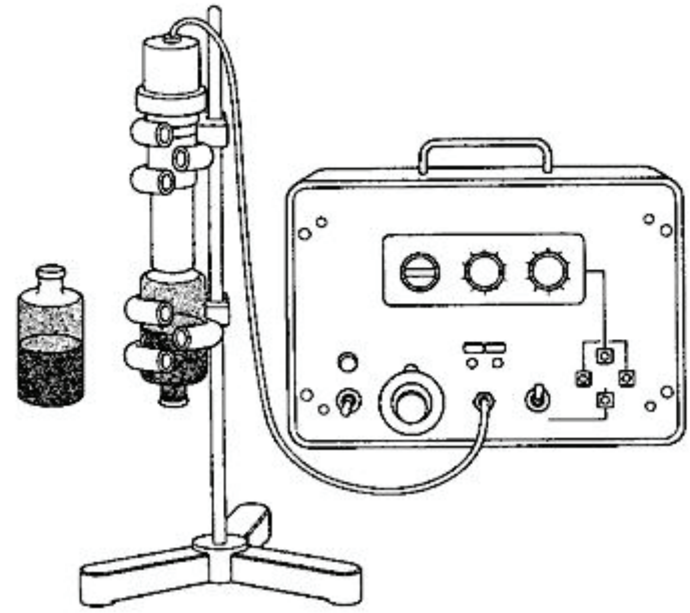
Procedure

a Support the G–M tube holder in a clamp so that the tube is facing downwards towards the neck of the bottle.

b Allow the bottle to stand for at least 10 minutes. Take the background count by running the counter for at least 30 s. This is done with the bottle in position, because some of the count will come from the lower layer. You can do this before the experiment or some time after it has finished.



Alternatively, the G–M tube can be clamped horizontally with the window close to the upper layer.



c Shake the bottle vigorously for about 15 s to mix the layers thoroughly.

d Place the bottle in the tray.

e As soon as the two layers have separated, start the count and start the stop-clock.

f Record the time from the beginning of the experiment (i.e. the “time of day” for the sample).

g Record the count every 10 s, or record it for 10 s every 30 s.

h Run the experiment for about five minutes – ample time to reveal the meaning of the term half-life and to illustrate the decay process.

i Provided that you leave a few minutes between each attempt, you can repeat the experiment. In five minutes the activity of the protactinium in the aqueous layer grows to 15/16 of its equilibrium value.

j It is possible to record the growth to equilibrium. Do this by moving the G–M tube so that the aqueous layer at the bottom of the bottle is immediately above the end window of the G–M tube.

Teaching notes

1 See **The chemistry of the protactinium generator** for an explanation of how it works.

2 Get the students to make a table of count rate against time, and correct it for background count. The first 10 s reading should be allocated to a time of zero.

3 Get the students to plot a graph of count rate against time. They should draw a smooth curve through the points.

First point out the general pattern – that the count rate decreases with time. Then look for an exponential trend – that the best-fit curve always takes the same amount of time to halve.

Get students to measure the half-life from the curve.

Point out the random nature of the points: although the decay follows a pattern, there is an element of randomness and it is not perfectly predictable.

4 “How science works” extension: This experiment provides an opportunity to assess the accuracy of the measured half-life value and how the random nature of decay affects the answer.

The commonly accepted value for the half-life of protactinium is 72 s.

Explore different ways in which a half-life value can be obtained from this apparatus:

- Amend the procedure described above so that, instead of a scaler (counter), a ratemeter is used. One student just records the time that it takes for the count rate to halve. This will provide a very approximate value.

- Repeat the experiment with several members of the class timing how long it takes for the count rate to halve. There is likely to be considerable spread in results across the group and the mean result may differ from the accepted value for half-life.
In each case, ask students to identify errors and uncertainties in their measurement(s) and to suggest ways in which these could be reduced.

For example, ask: “How does the random nature of the decay affect the measured count rate when the count is low, or high, compared with the background count?

- Either you or your students may suggest a graphical method as an improvement. The procedure described in the main experiment above could then be carried out and the accuracy of the half-life value assessed and evaluated.

Radioactive materials raise significant safety issues, providing an opportunity to discuss the value and use of secondary data sources.

This experiment was safety tested in February 2007.

Related guidance notes

- **Managing radioactive materials in schools**
- **Developing a model of the atom: radioactive atoms**
- **Exponential decay of a radioactive substance**
- **Some useful equations for half-lives**
- **The chemistry of the protactinium generator**

Simple model of exponential decay

Class experiment

In this activity, students model radioactive decay using coins and dice. By relating the results from the model to the experimental results in **Measuring the half-life of protactinium**, students can see that the model helps to explain the way in which a radioactive substance decays. The model provides an insight into what might be happening in radioactive atoms.

This activity is a good analogy for radioactive decay because it is based on probability. The decaying trend will be noticeable and so too will its random nature.

Apparatus and materials

- Pennies or other coins, plentiful supply
- Dice, plentiful supply (optional)

Technical notes

The more coins each student has, the better the analogy for radioactive decay. You could use as few as one per student to keep it simple. Any more than four is quite difficult to manage.

Small coins will turn around more in their cupped hands.

A canvas bag containing 500 plastic cubes (each side 10 mm), each with one face identified, is available in the UK from Lascells, order code 60-010.

Safety

Read our **health and safety statement**.

Procedure

a Explain the procedure (as follows) to the class.

b Each student has a number of coins. This should be between one and four. They hold them in their cupped hands.

c On the instruction "shake", the students shake their coins for at least 5 s (they should ensure that the coins are moving around inside their cupped hands). On the instruction "stop", they stop shaking and open their hands with one hand flat and facing upwards so that they can see their coins.

d If any coins come down heads, they take them out of their palm and place them on the desk.

e On the instruction "show", they put up a number of fingers corresponding to the number of coins that they took out of their palm.

f Record this number on the board.

g They keep the remaining coins in their hands and repeat from step **c**. If you can arrange it so that you take a reading once every minute, then you can record the readings against time. It will then give results very similar to protactinium.

h Analyse the result by plotting a graph.

Teaching notes

1 You might want to appoint a counter and a scribe to count the coins and record the results.

2 Take care with how you ask students to signal the numbers – they may be tempted to add their own (rude) gestures.

3 Draw out the similarities with the protactinium experiment. The trend is the same and there is also some randomness. The close match between the results from this model and the results from **Measuring the half-life of protactinium** show that radioactive atoms have a chance of decaying in any fixed time.

4 Use the activity to explain the downward trend of the decay curve. Only coins that are left can "decay". There are fewer of them each time, so fewer will decay each time.

5 The activity raises the interesting question about how long a radioactive source will last and what happens to the last "atom".

6 An alternative to shaking the coins in students' palms is to flick them, but this takes longer.

7 You could repeat the experiment with small dice to give a longer half-life. Combining results (as outlined here) makes for a smoother curve.

This experiment was safety tested in May 2007.

Related guidance notes

- **Exponential decay of a radioactive substance**
- **Some useful equations for half-lives**

Managing radioactive materials in schools

Countries have national laws to control how radioactive materials are acquired, used and disposed of. These follow internationally agreed principles of radiological protection.

The following principles apply to schools:

- There should be someone at school designated to be responsible for the security, safety and proper use of radioactive sources.

- Sealed radioactive sources should be of a safe design and type suitable for school science.

- Sealed sources should be used whenever possible in preference to unsealed sources. Unsealed sources can only be justified when the scientific demonstrations would not be practicable using sealed sources.

- Records of all radioactive sources should be kept properly, showing what they are, when they were bought, when and by whom they have been used and, eventually, how they were disposed of.

- Radioactive sources should be used only when there is an educational benefit.

- Radioactive sources should be handled in ways that minimise both staff and student exposures.

- Sealed sources should be carefully checked periodically to make sure that they remain in a safe condition.

- The school should have a suitable radioactivity detector in good working order.

UK regulation and guidance
Generally, school employers will insist that you obtain their permission before acquiring new radioactive sources.

You must follow your employer's safety guidance relating to the use of radioactive sources. Most school employers will require you to use either SSERC or CLEAPSS safety guidance, as follows:

In Scotland, safety guidance for use of radioactive sources in schools is issued by the Scottish Schools Equipment Research Centre (SSERC) and is available to members through its website at www.sserc.org.uk.

In the rest of the UK and British Isles Crown Dependencies, guidance is available from CLEAPSS, the School Science Service. Its guidance document, L93, is freely available from its website, even to non-members. Download it from the bottom of the webpage at http://www.cleapss.org.uk/secfr.htm

In the UK,

- In classes where children are under the age of 16, the use of radioactive material shall be restricted to demonstrations by qualified science teachers, (which includes newly qualified teachers). However, closer inspection of devices containing low-activity sources, such as diffusion cloud chambers, is permitted provided the sources are fully enclosed within the devices and not removed during the inspection.

- Young persons aged 16 and over may use radioactive sources under supervision.

Although the use of radioactive material is regulated, it should not be used as an excuse to avoid practical work. As the ASE points out, “Using the small sources designed for school science gives a good opportunity to show the properties of radioactive emissions directly, and to discuss the radiation risks. Just as importantly, it is an opportunity to review pupils' perception of risks, as they are likely to have constructed their own understanding from a variety of sources, including science-fiction films and internet sites. If the work is restricted just to simulations, it may reinforce exaggerated perceptions of risk from low-level radiation.”

Summary of legislation (UK)

The following summarises the somewhat complicated legislative framework in which schools are expected to work with radioactive sources in the UK. However, teachers do not need to obtain and study this legislation; this has been done by CLEAPSS and SSERC, and it is incorporated into their guidance in plain English.

In the European Union, member states have implemented the 1996 EU Basic Safety Standards Directive (as amended), which in turn reflects the 1990 International Commission on Radiological Protection recommendations. In the UK, this has been done through the Radioactive Substances Act 1993 (RSA93) which controls the security, acquisition and disposal of radioactive material, and the Ionising Radiations Regulations 1999 (IRR99), which control the use of radioactive material by employers. Transport of radioactive material is controlled by the Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2007.

There are exemptions from parts of the RSA93 and schools can make use of the Radioactive Substances (Schools etc.) Exemption Order 1963, the Radioactive Substances (Prepared Uranium and Thorium Compounds) Exemption Order 1962 and others. These exemption orders are conditional. To make use of them and avoid costly registration with the Environment Agency (SEPA in Scotland or the Environment and Heritage Service in Northern Ireland), you must adhere to the conditions.

However, the way in which these laws are implemented in England, Wales, Northern Ireland and Scotland varies. Maintained schools (but not independent schools and colleges) in England and Wales must follow the official guidance from the Department for Children, Schools and Families (DCSF), or in Wales, the National Assembly Department for Children, Education, Lifelong Learning and Skills Training and Education, in administrative memorandum DES/WO AM 1/92. Most independent schools choose to follow this guidance too. In Scotland, the equivalent advice is to be found in SOED Circular 1166 (1987), and in Northern Ireland in *The Use of Ionising Radiations in Educational Establishments* 1986.

Currently, maintained schools in England must apply to the DCSF to obtain new sources . Maintained schools in Wales must apply to National Assembly Department for Children, Education, Lifelong Learning and Skills, schools in Northern Ireland must apply to the Department of Education Northern Ireland (DENI), and schools in Scotland must apply to Scottish Government Education Directorate. The Crown

Dependencies Jersey, Guernsey and Isle of Man are not part of the UK and must apply for permission from their own internal government departments responsible for education.

In England, Scotland and Wales, practical work with radioactive sources in schools is classified into three categories – A, B and C – in which C has the greatest level of restriction. Most schools operate in category C, which places a limit on sealed sources to a total holding of 1.1 MBq, with no one source to exceed 370 kBq. Unsealed sources are not permitted other than a few exceptions. Apart from thoriated gas mantles, thorium compounds are prohibited in category C work in Scotland. Elsewhere they are allowed in thorium powder radon generators for half-life. Protactinium generators and radium paint cloud chamber sources have also been withdrawn from use in Scotland, but they remain permitted for use elsewhere in the UK.

In the UK, if an employer carries out a practice with sources of ionising radiation, including work with radioactive isotopes that exceed specified activities (which is 100 kBq for Co-60, and 10 kBq for Sr-90, Ra-226, Th-232, Am-241 and Pu-239), the practice must be regulated according to the IRR99 and the employer must consult with a radiation protection adviser (RPA). Since 2005 the RPA has had to hold a certificate of competence recognised by the Health and Safety Executive. Education employers are unlikely to have staff with this qualification, so the RPA will usually be an external consultant.

Note: For higher risk work with radioactive material, the IRR99 requires designated areas, called controlled areas and supervised areas, to be set up if special procedures are needed to restrict significant exposure – “special” means more than normal laboratory good practice. It should never be necessary for a school to designate an area as controlled, and only in special circumstances would it be necessary to designate an area as supervised. The normal use of school science radioactive sources, including the use of school science half-life sources, does not need a supervised or controlled area.

Disposal of sources in the UK

Sources that become waste because they are no longer in a safe condition, or are no longer working satisfactorily, or are of a type unsuitable for school science, should be disposed of. In England and Wales the Environment Agency has produced a guidance document through CLEAPSS that explains the available disposal routes. Similarly, SSERC has produced guidance for schools in Scotland. Schools in Northern Ireland should refer to DENI.

Updated 1 April 2008

Making dry ice

Solid carbon dioxide (CO_2) is known as dry ice. It sublimes at –78 °C, becoming an extremely cold gas. It is often used in theatres or nightclubs to produce clouds (looking a bit like smoke). It is more dense than the air, so it stays low. It cools the air and causes water vapour in the air to condense into tiny droplets, hence the “clouds”.

It is also useful in the physics (and chemistry) laboratory.

Safety

Wear eye protection and gauntlet-style leather gloves when making or handling solid carbon dioxide.

Uses

Dry ice has many uses. As well as simply watching it sublime, you can use it for cloud chambers, dry ice pucks, cooling thermistors and metal wire resistors in resistance experiments. It can also be used in experiments related to the gas laws.

Obtaining dry ice

There are two main methods of getting a source of dry ice:

1 Using a cylinder of CO_2

It is possible to make the solid “snow” by expansion before the lesson begins and to store it in a wide-necked vacuum flask.

Remember that the first production of solid carbon dioxide from the cylinder may not produce very much, because the cylinder and its attachments have to cool down.

What type of cylinder, where do I get CO_2 and what will it cost?

A CO_2 gas cylinder should be fitted with a dip tube (also called a “siphon type” cylinder). This enables you to extract from the cylinder bottom so that you get CO_2 in its liquid form, not the vapour.

Note: A plain black finish to the cylinder indicates that it will supply vapour from above the liquid. A cylinder with two white stripes, diametrically opposite, indicates that it has a siphon tube and is suitable for making dry ice.

A cylinder from British Oxygen will cost about £80 per year for cylinder hire and about £40 each time you need to get it filled up. (The refill charge can be reduced by having your chemistry department cylinders filled up at the same time.)

Don't be tempted to get a small cylinder – it will run out too quickly.

If the school has its own CO_2 cylinder, there will be no hire charge, but you will need to have it checked from time to time (along with fire extinguisher checks). Your local fire station or their suppliers may prove to be a good source for refills.

CLEAPSS leaflet PS45, **Refilling CO_2 cylinders**, provides a list of suppliers of CO_2.

A dry-ice attachment for the cylinder

Dry-ice disks can be made using an attachment that fits directly onto a CO_2 cylinder with a siphon tube. Section 13.3.1 of the CLEAPSS *Laboratory Handbook* explains the use of this attachment (sometimes called Snowpacks or Jetfreezers). This form is most useful for continuous cloud chambers and low-friction pucks.

You can buy a Snowpack dry-ice maker from Scientific and Chemical. Type “dry ice” into its cat no/description box. The product number is GFT070010 .

VWR International sells Snowpacks through its UK distributor. The version that makes 30 g pellets of dry ice has catalogue number 3285042/02.

Philip Harris sells similar products. See catalogue number C7A57812. (The dry-ice attachment comes with safety gloves.)

2 Buying blocks or pellets

Blocks of solid CO_2 or granulated versions of it can be obtained fairly easily by searching on the internet. Local stage supply shops or universities may be able to help. Solid CO_2 usually comes in expanded foam packing. You can keep it in this in a deep freeze for a few days.

The dry-ice pellets come in quite large batches. They have a number of uses in science lessons so it is worth trying to coordinate the activities of different teachers to make best use of your bulk purchase.

Health and safety statement

See the health and safety notes in each experiment. This is general guidance.

Health and safety in school and college science affects all concerned: teachers and technicians, their employers, students, their parents or guardians, and authors and publishers.

These guidelines refer to procedures in the UK. If you are working in another country you may need to make alternative provision.

Health and safety checking

As part of the reviewing process, the experiments on this website have been checked for health and safety. In particular, we have attempted to ensure that:

- all recognized hazards have been identified;
- suitable precautions are suggested;
- where possible, the procedures are in accordance with commonly adopted model (general) risk assessments;
- where model (general) risk assessments are not available, we have done our best to judge the procedures to be satisfactory and of an equivalent standard.

Assumptions

It is assumed that:

- the practical work is carried out or supervised by a qualified science teacher with adequate knowledge of physics and the equipment used;
- practical work is conducted in a properly equipped and maintained laboratory;
- rules for student behaviour are strictly enforced;
- equipment is regularly inspected and properly maintained, with appropriate records being kept;
- care is taken with normal laboratory operations, such as heating substances and handling heavy objects;
- good laboratory practice is observed;
- eye protection is worn whenever risk assessments require it;
- hand-washing facilities are readily available in the laboratory.

Teachers' and their employers' responsibilities

Under the Health and Safety at Work Act and related regulations, UK employers are responsible for making a risk assessment before hazardous procedures are undertaken or hazardous materials are used. Teachers are required to co-operate with their employers by complying with such risk assessments. However, teachers should be aware that mistakes can be made and, in any case, different employers adopt different standards.

Therefore, before carrying out any practical activity, teachers should always check that what they are proposing is compatible with their employer’s risk assessments and does not need modification for their particular circumstances. Any rules or restrictions issued by the employer must always be followed, whatever is recommended here. However, far fewer exercises are banned by employers than is commonly supposed.

Be aware that some activities, such as the use of radioactive material, have particular regulations that must be followed.

Reference material

Model (general) risk assessments have been taken from, or are compatible with:
CLEAPSS *Laboratory Handbook* (see annually updated CD-ROM)
ASE 2006 *Safeguards in the School Laboratory* 11th edn
ASE 2001*Topics in Safety* 3rd edn
ASE 2006 (and later) safety reprints

Procedures

Clearly, you must follow whatever procedures for risk assessment your employers have laid down. As far as we know, almost all of the practical work and demonstrations **on the Practical Physics website** are covered by the model (general) risk assessments detailed in the above publications, so in most schools and colleges you will not need to take further action, other than to consider whether any customisation is necessary for the particular circumstances of your school or class.

Special risk assessments

Only you can know when your school or college needs a special risk assessment. Thereafter, the responsibility for taking all of the steps demanded by the regulations lies with your employer.

External websites

The Nuffield Foundation and the Institute of Physics are not responsible for the content of external websites that are linked from **Practical Physics**.

Radioactive sources: isotopes and availability

In the UK, education suppliers stock only these three isotopes in sealed sources:

cobalt-60	pure gamma (providing the low-energy betas are filtered out)
strontium-90	pure beta
americium-241	alpha and some gamma

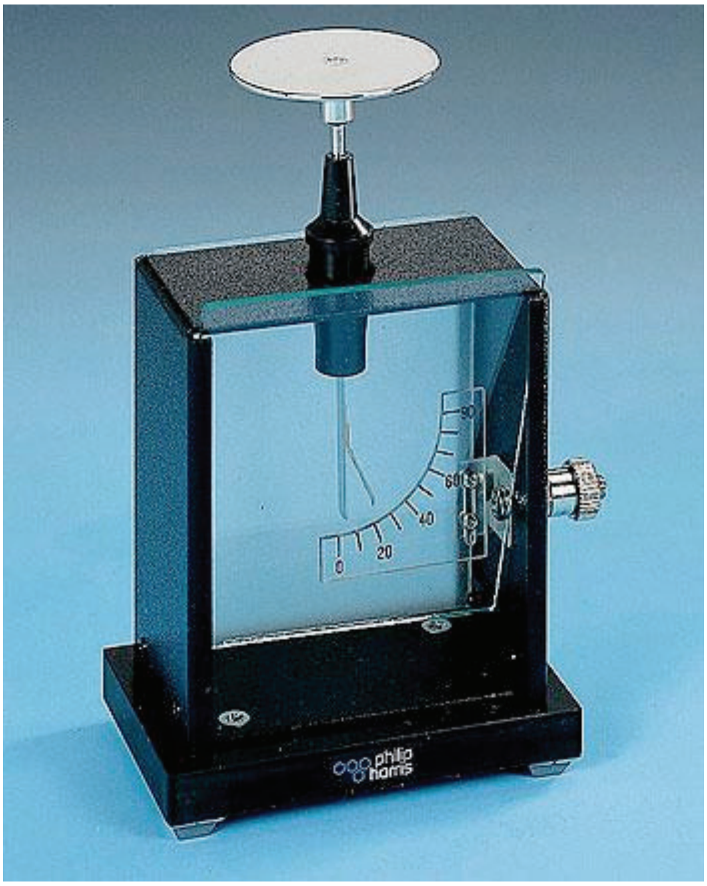
They are shown with the types of radiation that they emit.

However, you may have other sources in your school or local authority and, as long as you follow your school safety policy and local rules, you can use these in schools. The ones that are useful for practical work are:

radium	alpha, beta and gamma
plutonium-239	pure alpha
cesium-137	beta, then gamma (from its decay product, metastable Ba-137)

For safety information, see **Managing radioactive materials in schools**.

Using an electroscope



A gold-leaf electroscope measures the potential difference between the leaf and the base (or earth). The leaf rises because it is repelled by the stem (support). The leaf and its support have the same type of charge. A typical school electroscope will show a deflection for a charge as small as 0.01 pC (picocoulomb, 1x10^{-12} coulombs, equivalent to the charge on more than 6 million electrons).

Charging an electroscope

There are a number of ways to charge an electroscope. They include:

Charging by contact. Rub an insulator to charge it up. Then stroke it across the top plate of the electroscope. This will transfer charge from the insulator to the electroscope. This method is direct and clear to students. However, the charge left on the electroscope will not always leave it fully deflected.

Charging by induction. This is a quick way to get a larger charge onto the electroscope. However, it can look a bit magical to students, so it should be used with some care.

Rub an insulator to charge it up. Bring it close to the top plate of the electroscope, but don’t let it touch. This will induce the opposite charge on the plate of the electroscope, leaving a net charge on the gold leaf, which will rise. Now touch the plate with you finger momentarily to earth it (still holding the charged insulator near the top plate). The charge on the top plate will be neutralised but there will still be a charge on the gold leaf. Let go of the plate and then take the charged insulator away. The charge that had been pushed down to the gold leaf will now redistribute itself over the plate and the leaf, leaving the whole thing charged. The leaf will show a good deflection.

Charging with an EHT or Van de Graaff generator. You can use a flying lead connected to one of these high-voltage sources to charge up the gold-leaf electroscope. This is quick, effective and obvious to students. The other terminal of the supply should be earthed. Connect the flying lead to the supply through a safety resistor.

Detecting small currents

The electroscope can be used to demonstrate that a small current is flowing in a circuit (e.g. in experiments to show the ionisation of the air).

Using the hook rather than the plate makes the electroscope more sensitive to small amounts of charge. A charge of around 0.01 pC will cause a noticeable deflection of the gold leaf. Thus it is possible to watch it rise (or fall) slowly due to a current as small as 1 pA.

Put the electroscope in series (as though it were an ammeter). Any charge that flows through the circuit will move onto the electroscope, making the gold leaf rise. You may need to discharge the electroscope when you first switch on the power supply because there will be an initial movement of charge due to the capacitance in the circuit.

Alternatively, you can use the electroscope as a source of charge and watch it discharge – it is like a capacitor with its own display. Charge it up and then connect it into a circuit. If the circuit conducts, the electroscope (capacitor) will discharge and, at the same time, the leaf will display how much charge is left.

Using the electroscope as a voltmeter or electrometer

The electroscope has a very high (as good as infinite) resistance. If you earth its case, the electroscope measures potential so it is well suited to detecting potentials in electrostatic experiments. Without earthing, the quality that it measures is charge. This is related to potential difference (pd) (by its capacitance, C, i.e. $V = Q/C$). However, it isn't the same as pd, because the capacitance can vary a lot – even during an experiment. Capacitance depends on the position of the electroscope, people nearby and so on.

So although the electroscope is useful as an indication of a voltage, it isn't a reliable means of measuring it.

Cosmic radiation

School electroscopes are open to the air (more refined ones are in a vacuum). Cosmic radiation will ionise this air and cause a small leakage current, so the electroscope will discharge over time. Historically the discharging of electroscopes led to the suggestion of the existence of cosmic radiation. Victor Hess and Carl Anderson shared the Nobel Prize for Physics in 1936 for discoveries related to cosmic radiation.

First models of the atom

As students start experiments on ionisation, they will have a fairly basic model of atoms and molecules, as portrayed by the simple kinetic theory. They will know that solids, liquids and gases are made up of atoms and molecules. They may think of these as round blobs with no internal structure. These particles exert attractions on each other at short ranges of approach and, necessarily, repulsions at very short range. They bounce off each other in elastic collisions (kinetic energy is always conserved). More advanced students may understand that this is because the forces are the same on the way in as they are on the way out.

They will have heard of ions – probably in the context of chemical reactions, solutions and electrical conductivity. However, using ions to explain sparks may be a new idea to them. Ionisation and sparks show that electrons are easily knocked off neutral atoms and molecules. In these collisions, kinetic energy is not conserved – some of it is lost to remove the electrons. Thus the collisions are inelastic. This shows that the energies needed to remove electrons are of the order of the kinetic energy of a very fast moving particle (a few hundred metres per second).

Students' picture of the atom will develop. They will learn that it contains electrons, which are fairly easily detached. There must also be some positive material, probably holding most of the mass of the atom. The atom is held together in some unknown way.

How clouds form

Clouds form in the atmosphere when warm, wet air is pushed up. As the air goes higher its pressure decreases and it gets colder. The colder air cannot contain so much water vapour and the air becomes supersaturated with vapour. Given the right conditions, some of the vapour condenses to form water droplets in a cloud.

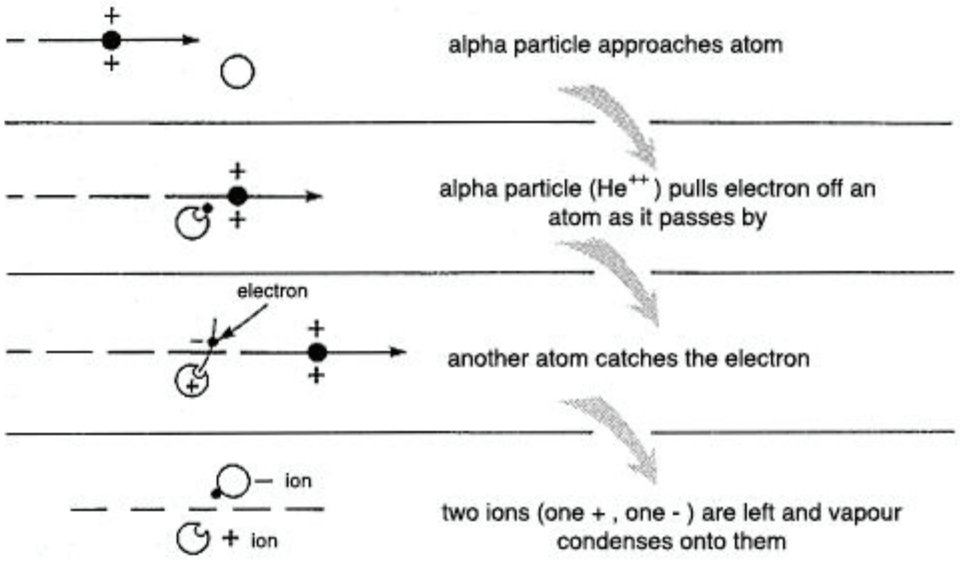
The droplets need something to form around. An extremely small droplet of just a few molecules cannot form a cloud all by itself. Its molecules would escape from each other again. If the air contains attractive particles (usually minute particles of salt) that the water can wet, a droplet will start to form. The salt particles serve as a condensation nucleus on which larger drops can grow.

A similar process is put to use in a cloud chamber containing alcohol vapour. Ions in the air can serve as excellent condensation nuclei. The alcohol molecules are electrically “oblong” with positive and negative charges at the ends, so they can cluster easily round a charged particle. The other small particles can be cleared out. This prevents droplets from forming into unwanted clouds, even when the air is supersaturated. Instead, the droplets form on the trail of ions left behind by ionising radiation, typically an alpha particle.

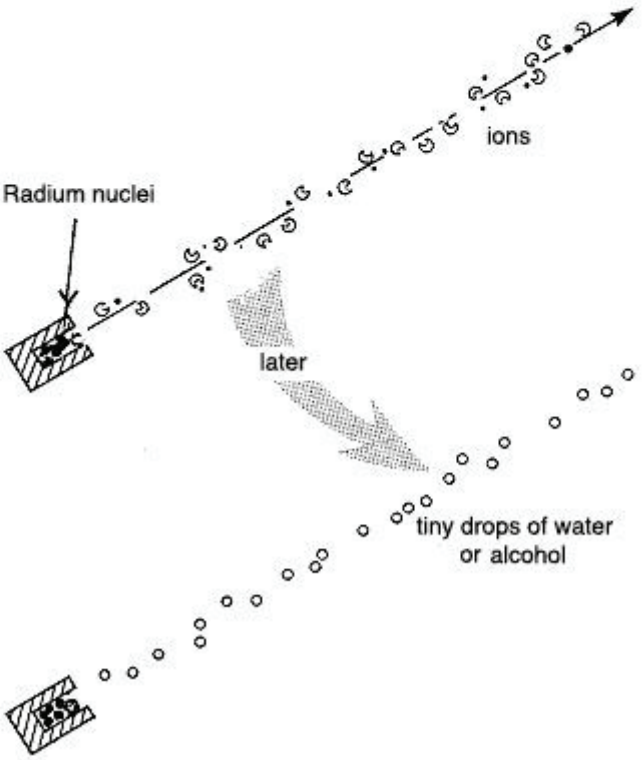
Alpha-particle tracks

Nuclear “bullets” from radioactive atoms make the tracks in a cloud chamber. They hurtle through the air, “wet” with alcohol vapour, detaching an electron from atom after atom and leaving a trail of ions in their path. Tiny drops of alcohol can easily form on these ions to mark the trail.

The trail of ions is made up of some “air molecules” that have lost an electron (leaving them with a positive charge) and some that have picked up the freed electrons, giving them a negative charge.



There is no sighting of the particle that caused the ionisation because it has left the scene before the condensation happens. If you count the number of droplets then an alpha particle might produce 100 000 pairs of ions by pulling an electron from 100 000 atoms.



Nucleur “bullets” forming a trail of ions, which are condensation nuclei

This is rather like a cannon ball that is fired through a field of ripe wheat. If you are watching from a helicopter, the ball moves too fast for you to see it and you will hardly notice the trail of broken stalks. Wait a few minutes and the track will be marked by a line of dark birds settled on the broken stalks. (This story is said to be due to Andrade.)

When the alpha particle has lost all of its energy in collisions with the “air molecules”, it stops moving and is absorbed.

Evidence for the hollow atom

The main and first evidence for the hollow atom came from Rutherford's alpha particle scattering experiment (see details on the Practical Physics website). However, the first evidence that students see for a hollow atom often comes from cloud-chamber photographs. Although this may be historically back to front, it is reasonable to use these photographs as the first indication that atoms are mainly empty.

Chronology of evidence

Rutherford had devised his model of a nuclear atom by 1910, before alpha-particle tracks were photographed in cloud chambers (c1911). However, he and Wilson worked in the same laboratory, so it is likely that Rutherford had seen tracks in cloud chambers.

The evidence provided by cloud-chamber photographs and the inferences that can be made are extremely useful, whether you present them as preparation for the Rutherford model or follow-up support for it.

Evidence from cloud chambers

Most of the time there is just a straight track produced when an alpha particle passes through the cloud chamber, producing ions. Mostly, these ions are produced by inelastic collisions with electrons in neutral particles. An alpha particle will have around 100 000 inelastic collisions before it runs out of kinetic energy. The number of collisions shows that electrons are easily removed.

The straightness of the tracks shows the following:

- An electron has a mass that is much smaller than the mass of an alpha particle (now known to be about one-seven thousandth of the size).

- The atom is hollow: each straight track represents about 100 000 collisions without any noticeable deviation. All of these missed anything with significant mass. During a session, the class might observe 1000 tracks between them, all of which are straight. Therefore, in all of these 100 million collisions with atoms, the alpha particles never hit anything with significant mass, so most of the atom is empty.

However, students will see photographs that show large deflections of alpha particles. These are rare events (requiring thousands of photographs to be taken). They show that:

- there is something in an atom that has a mass that is similar to the mass of an alpha particle – only a target with a comparable mass could cause a large deviation;

- this mass is very concentrated – the rareness of the forked tracks shows that most alpha particles miss this massive target.

Evidence from alpha-particle scattering

The hollowness of the atom is treated more quantitatively in the Rutherford scattering experiment. In this, 99.99% of the alpha particles are undeflected. This gives an indication of how tightly the positive charge of the nucleus is packed together.

Classroom management in semi-darkness

There are some experiments that must be done in semi-darkness. You need to plan carefully for such lessons. Ensure that students are clear about what they need to do during the activities and that they are not given unnecessary time. Keep an eye on what is going on in the class and act quickly to damp down any inappropriate behaviour before it gets out of hand.

Shadows on the ceiling will reveal movements that are not in your direct line of sight.

The nature of ionising radiation

Students' models of each type of radiation will develop through this topic. They will start with an idea of a generalised invisible radiation. As they see more evidence for the nature of the types of radiation, their model will become more sophisticated. This will be reflected in the developing language that you use to describe the radiation:

1. The radiation comes from ***radioactive materials*** and causes ionisation: it is ***ionising radiation***.

2. Natural radioactive materials produce three types of ionising radiation: ***alpha***, ***beta*** and ***gamma radiation***.

3. ***alpha*** and ***beta*** radiation are made up of streams of charged ***particles*** – alpha particles and beta particles. ***Gamma*** radiation is an electromagnetic wave.

4. An ***alpha particle*** is a ***helium ion*** (an atom that has lost two electrons), He^{2+}. A ***beta particle*** is a fast-moving electron, e^{-}.

5. an alpha particle is a ***helium nucleus*** (because it only has two electrons per atom). all three types of radiation originate in the nuclei of atoms.

Eventually, the properties and nature of alpha, beta and gamma radiation can be summarised as follows:

	alpha	**beta**	**gamma**
property	highly ionising	fairly ionising	weakly ionising – depends on intensity
	short range in air (3–5 cm)	medium range in air (~15 cm)	long range – inverse square law
	stopped by paper	stopped by lead or thick aluminium	attenuated by thick lead
	deflected slightly in magnetic field	deflected in magnetic field	undeflected in electric and magnetic fields
	deflected in electric field	deflected in electric field	
nature	positive charge	negative charge	no charge
	large mass (same as helium nucleus)	small mass	
identity	helium nucleus	Fast-moving electron	High-frequency electromagnetic wave

At each stage in this developing picture, you can link the properties of the type of radiation with its nature. Alpha radiation is highly ionising because of the large

momentum, though relatively modest speed (~10^7 m/s), of the alpha particles and their double positive charge. However, given its propensity to interact with atoms (in the air and in solids), it has a shorter range and lower penetrating power than the other two types of radiation.
Beta radiation is made up of a stream of beta particles moving extremely fast (about 98% of the speed of light). They have less momentum than alpha particles and are less ionizing, tending to pass through the air and matter more easily than alpha particles.

Beta particles are noticeably deflected in a magnetic field – much more so than alpha particles, whose deflection cannot easily be measured in a school laboratory. This is because the beta particles have a smaller momentum and experience a bigger force because they are moving faster. (Although they also have a smaller charge, their speed is more than twice as much as that of an alpha particle.)

The deflection of alpha particles can be more noticeable in an electric field. Here the force depends on the charge but not on the speed.

Gamma radiation is an electromagnetic wave. This means that it has no charge and is not deflected by magnetic or electric fields. It is weakly ionising and its effects on matter depends, among other factors, on the intensity of the radiation.

The chemistry of the protactinium generator

The first steps of the uranium-238 series are involved in this experiment.

$$\mathrm{U}^{238}_{92} \longrightarrow \mathrm{Th}^{234}_{90} \xrightarrow{\beta} \mathrm{Pa}^{234}_{91} \xrightarrow{\beta} \mathrm{U}^{234}_{92}$$

The aqueous solution (at the bottom of the bottle) contains the uranium-238, its daughter thorium-234 and the short-lived granddaughter protactinium-234.

Uranium and protactinium both form anionic chloride complexes but thorium does not. At high hydrogen ion concentrations, these complexes will dissolve in the organic layer (which is floating on top of the aqueous solution).

When you shake the bottle, about 95% of the short-lived granddaughter (protactinium) and some of the uranium will be dissolved in the organic layer. The thorium stays in the aqueous layer.

Radioactivity is a property of the innermost nucleus of the atom, so it is not affected by chemical combination.

The granddaughter (in the organic layer) decays without any more being produced by its parent (thorium), all of which is still in the aqueous layer. It emits beta particles, which travel through the plastic wall of the bottle. Isolating the protactinium in the top (organic) layer allows it to decay without any top-up from its parent (thorium).

The radiation from the thorium and uranium should not interfere with the results, for two reasons:

- The counter does not detect the alpha particles from the uranium or the low-energy beta particles from the thorium; it only records the high-energy (2 MeV) beta particles from the granddaughter (protactinium).

- The uranium-238 decays with an extremely long half-life. It yields a meagre, almost constant, stream of low-energy alpha particles. Its daughter, thorium-234, decays with a half-life of 24 days. During the length of this experiment the decay rate can be assumed to be constant. If these two isotopes contribute to the count at all, it will be accommodated in the background count. The stockpile of thoruim is also constantly topped up in the aqueous layer as long as the protactinium is present with the thoruim.

Developing a model of the atom: radioactive atoms

At this stage, pupils may regard atoms as the fundamental chemical particles. True, electrons can be chipped off an atom, and possibly all of an atom's electrons can be stripped off to leave a bare nucleus. However, according to the simple story, the nucleus is still fixed and determines the element by its charge, Ze.

Therefore to change one element into another – the alchemist's dream of lead into gold – would require a change of nuclear charge. At first sight this seems impossible because the nucleus is buried deep in the atom bound together by tremendous forces. However, it does happen in radioactive elements.

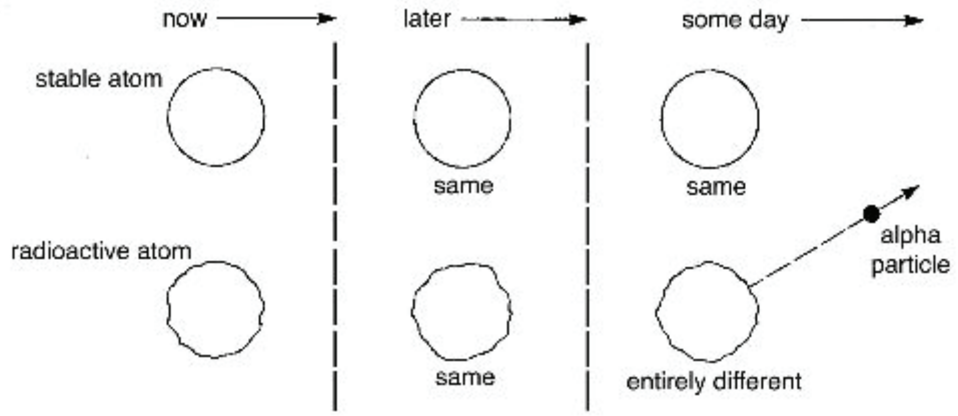
Soon after the discovery of radioactivity in 1896 by Bequerel, Marie Curie and her husband, Pierre, discovered a new element, which they named radium. They extracted dangerously large samples of radium from vast quantities of rock and they experimented on its radioactive behaviour.

You could say:

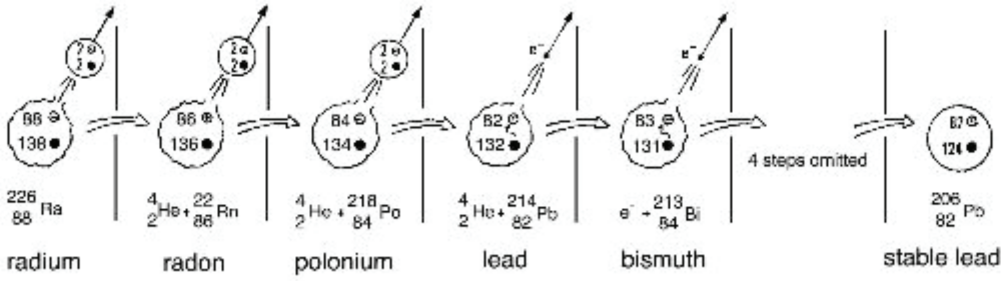
Radioactive atoms do not just stay there as atoms of ordinary copper do; they are completely different: they are unstable, they suddenly break up, flinging out a particle such as an alpha particle, becoming an atom of a different element.

A radium atom remains a radium atom, with the chemical behaviour of a heavy metal, until it suddenly hurls out this alpha particle. (The alpha particle has such a huge energy that it must come from the nucleus.) The remainder of the radium atom is no longer a heavy metal but a quite different element. This "daughter" of radium is an atom of a heavy inert gas, the end of the helium, neon, argon, krypton, xenon series. It is called radon. The atomic masses have been measured directly: radium-226, radon-222 (a difference of 4, suggesting that the lost alpha particle is a helium nucleus). Separate measurements confirm this.

When you have a mixture of a parent element and a daughter element that have different chemical properties, then they can be separated by ordinary chemical methods.



Radon gas is itself unstable and radioactive. Each of its atoms suddenly, at an unpredictable moment, hurls out an alpha particle. The remainder is a new atom, very unstable, which is called polonium, the “daughter” of radon and the “granddaughter” of radium. The series continues through several more radioactive elements and stops at a stable form of lead. It does not begin with radium: it begins with uranium several stages earlier. Radioactive uranium (Z=92) has turned into lead (Z=82).

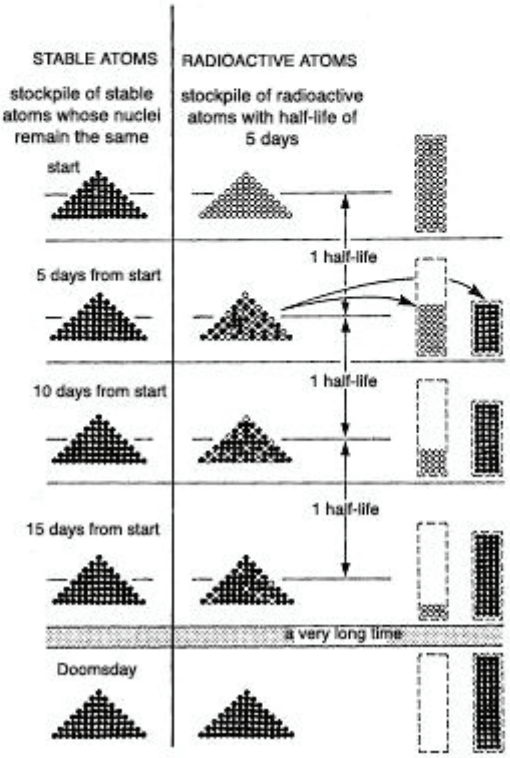


Making unstable atoms

A century ago, radioactivity was a peculiarity of a few, mostly heavy, elements: the last few at the end of the Periodic Table. Nowadays, scientists can bombard samples of lighter elements with high-speed, high-energy protons or neutrons, provided directly or indirectly by an accelerator. They can make unstable isotopes of every element in the periodic table. This has opened up the field of nuclear chemistry. Radioactive isotopes behave chemically like their stable isotopes and can be mixed with them. Their progress as radioactive tags can be traced, like luggage labels, following the progress of a “labelled” isotope through the human body or an industrial process.

Half-lives

All of the unstable members of these strange families have a constant, reliable characteristic: the atoms show no signs of aging, or growing weaker, however long they last. Each radioactive element has a constant chance of breaking up in each succeeding second. This is described by a useful length of time: the half-life of the radioactive element. For each individual atom the betting is 50:50 for and against its breaking up at any time during one half-life from a particular moment. The break-up seems to be controlled by pure chance. That chance does not change and make the break-up more likely for atoms that need to survive longer.



For radium the half-life is 1650 years. Start with 1000 mg of radium now and 1650 years later you will have only 500 mg left. After a further 1650 years only 250 mg will be left, and so on. For radium's "daughter", radon -222, the half-life is 3.8 days. In less than four days half of the radon gas will have disappeared. You will find helium gas there instead, with the solid products.

The instability appears to be something inherent in the nuclear structure. Nowadays, taking a wave view of the behaviour of nuclear particles, you can picture a stationary wave pattern defining the life of an alpha particle inside the nucleus. However, the wave is not completely confined – it leaks through the potential barrier round the nucleus and runs on as a faint wave outside. The wave is interpreted as describing probabilities of locations; it is not a mechanical wave carrying energy and momentum.

While the alpha particle is expected to be inside the nucleus, there is a chance of finding it one day outside, despite what would seem an insurmountable potential wall. That chance of the alpha particle being outside, being emitted, is definite and constant – a part of the defining wave property – as long as the nucleus lasts. It suggests that high-energy alpha particles go with a short half-life of the parent nucleus.

Exponential decay of a radioactive substance

One of the most important characteristics of radioactivity is that it decays exponentially.

This has two basic mathematical implications at this level:

1. The rate falls by a constant ratio in a given time interval. The time it takes to fall by a half is always the same. It also falls to a tenth in equally regular, but longer, time intervals.

2. The rate of decay is proportional to the amount that is left. This can be seen in the **Simple model of exponential decay** experiment. The number of coins that decay in any “shake” is proportional to the number that are left.

From these features you can argue, respectively, the following points:

1. The chance of an atom disintegrating is constant in time. Radioactive decay is a series of many chance events, all with an unalterable chance.

2. The rate of disintegrations is proportional to the total number of unchanged radioactive atoms at that moment. Both the rate and the stockpile die away exponentially with the same characteristic half-life.

Some useful equations for half-lives

The rate of decay of a radioactive source is proportional to the number of radioactive atoms (N) present,

$$\frac{dn}{dt} = -\lambda N$$

λ is the decay constant, which is the chance that an atom will decay in unit time. It is constant for a given isotope.

The solution of this equation is an exponential one, where N_0 is the initial number of atoms present:

$$N = N_0 e^{-\lambda t} \qquad (1)$$

Constant ratio

This equation shows one of the properties of an exponential curve: the constant ratio property.

The ratio of the value N_1 at a time t_1 to the value N_2 at a time t_2 is given by:

$$\frac{N_1}{N_2} = \frac{e^{-\lambda t_1}}{e^{-\lambda t_2}}$$

$$= e^{-\lambda(t_1 - t_2)}$$

In a fixed time interval, $t_2 - t_1$ is a constant. Therefore the ratio

$$\frac{N_1}{N_2} = \text{a constant}$$

So, in a fixed time interval, the value will drop by a constant ratio, wherever that time interval is measured.

Straight-line log graph

Another test for exponential decay is to plot a log graph, which should be a straight line.

From equation 1:

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

Therefore a graph of lnN against t will be a straight line with a slope of –λ.

Half-life and decay constant

The half-life is related to the decay constant. A higher probability of decaying (bigger λ) will lead to a shorter half-life.

This can be shown mathematically.

After one half life, the number, N, of particles drops to half of N_0 (the starting value). So:

$$N = \frac{N_0}{2} \quad \text{when} \quad t = T_{1/2}$$

Then, by substituting in equation (1),

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

Taking natural logs of both sides gives:

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

$$\Rightarrow \ln 2 = +\lambda T_{1/2}$$

$$\Rightarrow T_{1/2} = \frac{0.693}{\lambda}$$