Chapter 5

NUCLEAR CHEMISTRY AND RADIOISOTOPES

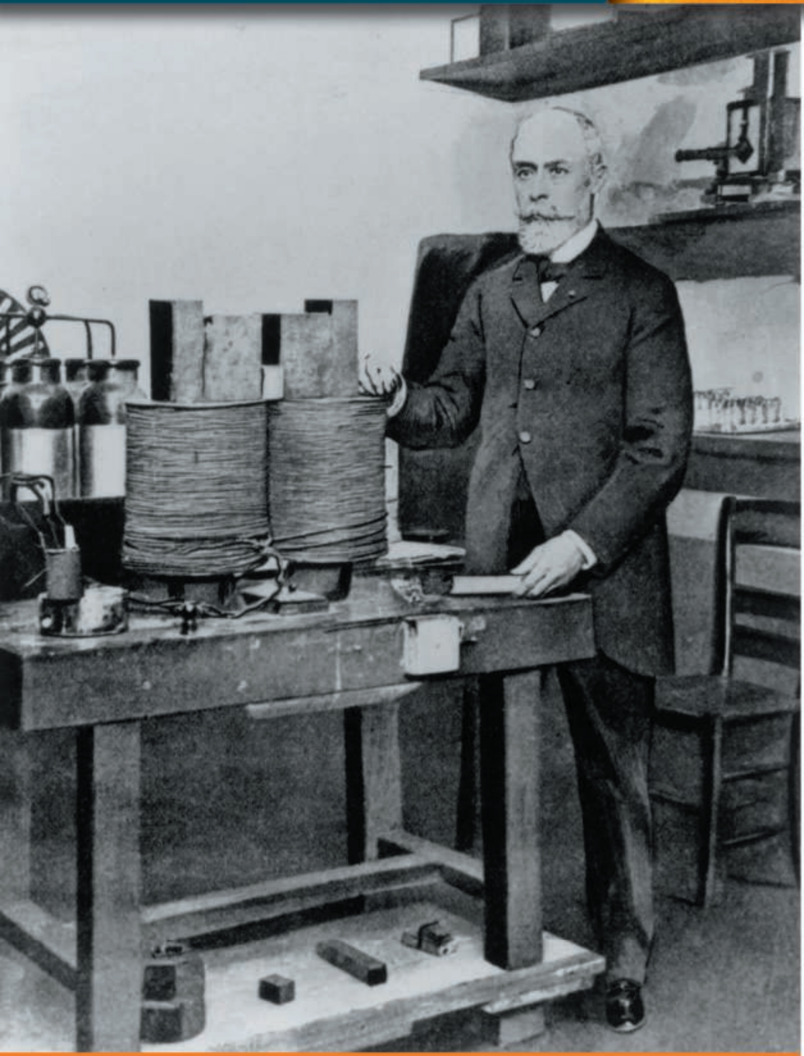


Figure 5.1

Henri Becquerel accidentally discovered that uranium ores gave out invisible rays. Elements that released these rays were termed 'radioactive'.

Introduction

Not all atoms are stable. Scientists discovered this fact only at the end of the nineteenth century. In Paris in 1896, Henri Becquerel accidentally discovered that uranium ores gave out invisible rays that darkened photographic plates. A few years later Marie and Pierre Curie discovered the radioactive elements polonium and radium and showed that thorium was also radioactive. By 1910, Marie Curie had succeeded in isolating very small samples of metallic radium.

In this chapter

5.1 NUCLEAR CHEMISTRY

Remember

Before beginning this section, you should be able to:
- describe atoms in terms of mass number and atomic number
- identify an appropriate model that has been developed to describe atomic structure

Key content

By the end of this section, you should be able to:
- distinguish between stable and radioactive isotopes, and describe the conditions under which a nucleus is unstable
- identify instruments and processes that can be used to detect radiation.

Figure 5.2
Marie Curie was a student of Henri Becquerel. She went on to win two Nobel Prizes for her discoveries about radioactivity and the discovery of two new radioactive elements (polonium and radium).

isotope: atoms of an element with the same atomic number but different mass number

atomic number (Z): the number of protons in a nucleus

Nuclear stability

The stability of the nucleus is related to the strength of the forces that hold the nuclear particles together. The protons and neutrons of the nucleus are called *nucleons*. The force that holds the nucleons together in the nucleus is called the *strong nuclear force*. The strong nuclear force (which operates over small nuclear distances) is independent of charge and is much stronger than the electrostatic repulsion force between protons.

Scientists have discovered that the ratio of neutrons to protons (n : p) in the nucleus is an indicator of nuclear stability. In stable, light elements the number of neutrons is generally the same as the number of protons. In the heavier elements, more neutrons are required to keep the nucleus stable. Generally:

- stable light elements ($Z \sim 1$–20): n : p ratio ~ 1.0 : 1
- stable heavy elements ($Z \sim 73$–83): n : p ratio ~ 1.5 : 1

Elements with $Z > 83$ are radioactive as their nucleus is unstable.

Examples:

Stable light element:

$^{24}_{12}Mg$ ($Z = 12$; $A = 24$; $N = 24–12 = 12$; magnesium-12 isotope has an n : p ratio of 12 : 12 = 1 : 1).

Stable heavy element:

$^{206}_{82}Pb$ ($Z = 82$; $A = 206$; $N = 206–82 = 124$; lead–206 isotope has an n : p ratio of 1.51 : 1)

Radioactive elements have neutron to proton ratios that vary from these stable ratios. There are no stable **isotopes** for elements with **atomic numbers** greater than 83 (bismuth).

These observations on neutron to proton ratios are summarised graphically in Figure 5.3. Note how the band of stable nuclei moves away from the n : p = 1 : 1 line as the elements get heavier. Note also that surrounding the stable band are bands of unstable radioactive isotopes whose n : p ratios are either too high or too low.

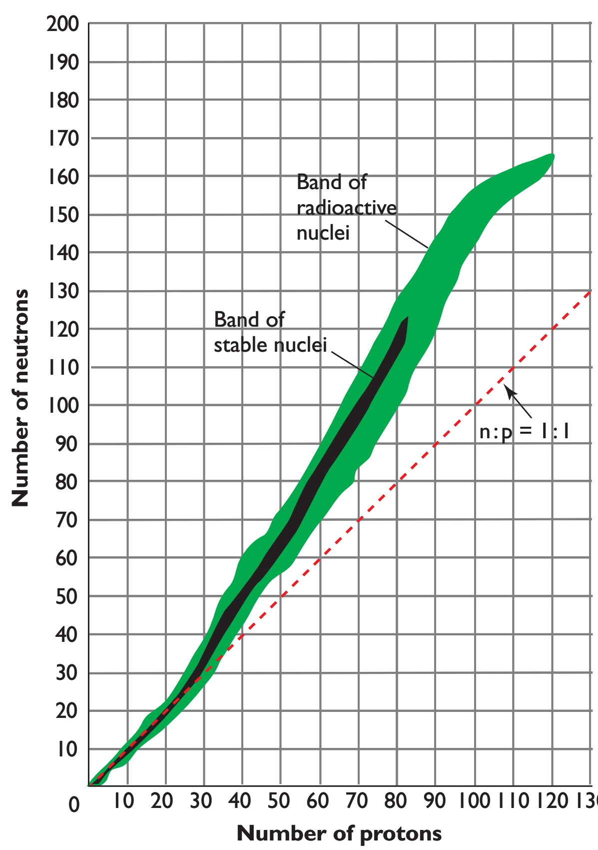


Figure 5.3
Stable, light elements have a n : p ratio of 1 : 1. For stable, heavy elements, this ratio rises to 1.5 : 1.

gamma rays: high energy electromagnetic radiation from the nucleus

alpha particle: a particle consisting of a helium nucleus

beta particles: fast moving electrons produced during nuclear decay

Radioactive elements emit particles or rays from their nucleus as they decay. In some cases the decay of a radioactive nucleus into a stable nucleus can occur in one step. In other cases, such as with uranium, many decay steps are involved before the nucleus becomes stable. Alpha, beta and **gamma rays** can be distinguished from one another by passing them through an electric field. Positive **alpha particles** are attracted towards the negative plate and negative **beta particles** are attracted to the positive plate. Gamma rays are unaffected by electric fields.

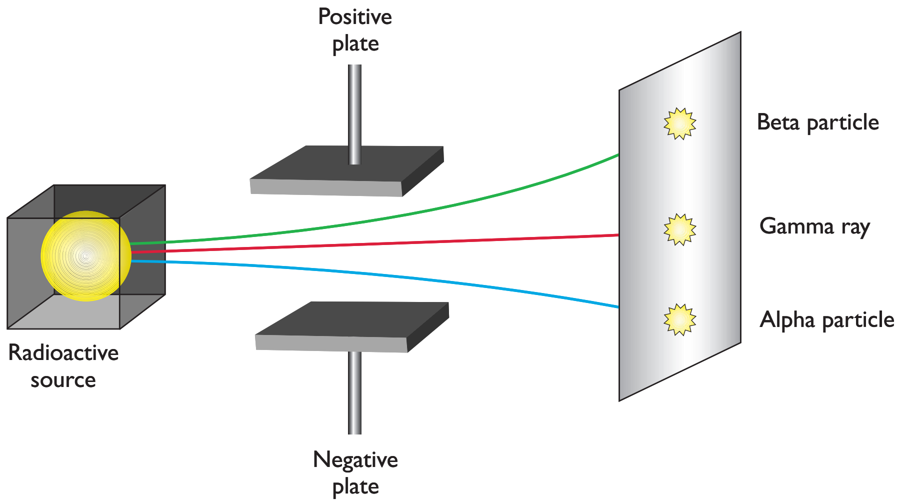


Figure 5.4
The electric field is used to separate alpha, beta and gamma rays on the basis of their charges.

Examples of nuclear decay

Consider the following examples of nuclear decay.

Alpha emission

Alpha particles are helium nuclei ($^{4}_{2}He$). They consist of two protons and two neutrons and are therefore positively charged. They are ejected from heavy, unstable nuclei so as to remove a surplus of protons and neutrons. The nucleus that forms may still be radioactive, in which case further decay reactions will occur. Alpha emission tends to occur in nuclei with atomic numbers greater than 83. In the following example the polonium-218 that forms from the alpha decay of radon-222, is still radioactive, and decays further by alpha (and beta) emission. Note that the nuclear equation shows that the atomic numbers (Z) are conserved (86 = 84 + 2) and the **mass numbers (A)** are conserved (222 = 218 + 4) in the decay.

mass number (A): the number of nucleons (neutrons + protons) in the nucleus

Example:
Alpha decay of radon-222

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

Beta emission

Beta particles are electrons ($^{0}_{-1}e$) that are released from the nucleus when a neutron decays into a proton and an electron. Beta decay occurs when the n : p ratio is too high due to a surplus of neutrons.

Example:
Beta decay of zirconium-97

$$^{97}_{40}Zr \rightarrow {}^{97}_{41}Nb + {}^{0}_{-1}e$$

Electron capture

Some unstable nuclei have a surplus of protons (n : p is too low) and to achieve stability they can capture an inner shell electron and convert a proton into a neutron. Beryllium-7 can transmute into lithium-7 in this way.

Example:
Electron capture by beryllium-7

$$^{7}_{4}\mathrm{Be} + ^{0}_{-1}\mathrm{e} \rightarrow ^{7}_{3}\mathrm{Li}$$

Gamma emission

Gamma ray (γ) emission accompanies many nuclear decay reactions. Gamma rays are high-energy electromagnetic rays. Gamma emission is a means of shedding excess energy as the nuclear particles rearrange. Note that the release of a gamma ray does not change the conservation of atomic and mass numbers in the nuclear equation.

Example:
Gamma emission from cobalt-60

$$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni} + ^{0}_{-1}\mathrm{e} + \gamma$$

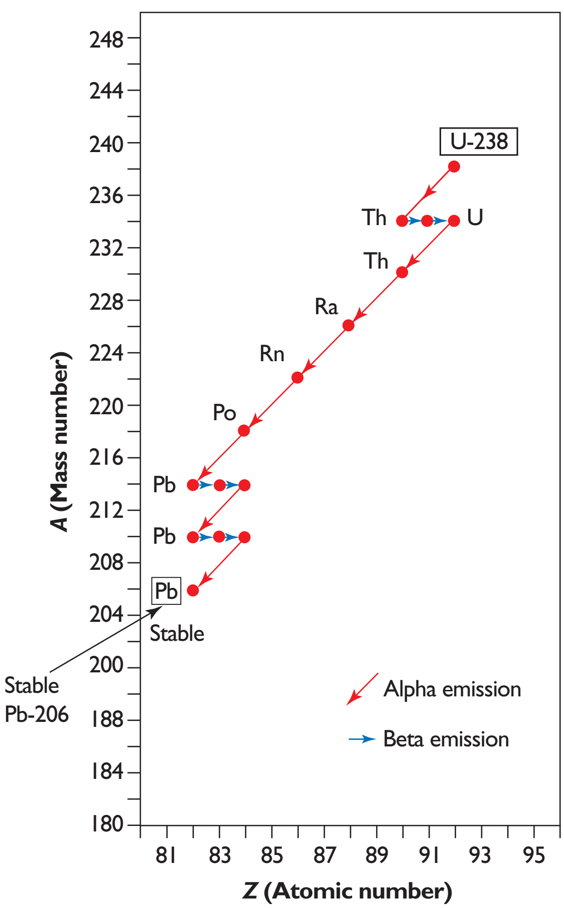


Figure 5.5
Uranium-238 decays through many steps to form lead-206. In this process eight alpha particles and six beta particles are emitted.

Uranium natural decay series

Uranium-238 and uranium-235 are naturally occurring radioactive isotopes. They decay by a series of alpha and beta emissions through radioactive intermediates until a stable isotope of lead is formed. This decay chain takes such a long time to reach the stable lead isotope that approximately half of the uranium-238 present at the formation of the Earth about 4.5 billion years ago still remains. The net nuclear equations are:

$$^{238}_{92}\mathrm{U} \rightarrow ^{206}_{82}\mathrm{Pb} + 8(^{4}_{2}\mathrm{He}) + 6(^{0}_{-1}\mathrm{e})$$

$$^{235}_{92}\mathrm{U} \rightarrow ^{207}_{82}\mathrm{Pb} + 7(^{4}_{2}\mathrm{He}) + 4(^{0}_{-1}\mathrm{e})$$

Figure 5.5 shows the decay series for uranium-238. Note that each alpha emission is shown by a diagonal line to the left and each beta emission by a horizontal line to the right.

Detecting radiation

The properties of nuclear radiation are used to detect their levels. As this radiation is dangerous to humans, it is important to monitor exposure. Radiation exposure is measured in several different units. The becquerel (Bq) is a unit of radioactivity equal to one nuclear disintegration per second. Because different types of radiation have different effects on the human body, another unit called the sievert (Sv) is used to measure radiation dosage in biological tissue.

The key properties that are used to detect nuclear radiation include the ability to:

- darken a photographic film
- cause electron excitation into energy 'traps' in the lattice of certain crystals
- penetrate materials to different extents
- cause ionisation in gases and vapours
- be deflected (or not deflected) by electric or magnetic fields.

Radiation dosage badges

Radiation dosage badges are worn by workers in the nuclear industry to monitor their radiation exposure. There are several types of badges, the most important being film badges and thermoluminescent dosimeters (TLDs).

Film badges

The film badges monitor high-energy beta rays as well as gamma and X radiation. On one side of the film is a sensitive (or 'fast') silver halide emulsion, and on the other a 'slow' emulsion. Low radiation doses will blacken the sensitive emulsion but not the slow emulsion. Higher doses will blacken the slow emulsion. The badges are analysed regularly to assess radiation dose. Alpha rays have very low penetrating ability (i.e. they travel only several centimetres in air and will be stopped by a sheet of paper) and are not normally monitored.

Thermoluminescent dosimeters (TLDs)

Certain crystals such as aluminium oxide or lithium fluoride absorb strong beta or gamma radiation, and this absorbed energy causes electrons to be excited to higher energy states where they become trapped in 'trapping centres'. The radiation dose is determined by releasing the trapped electrons (using laser radiation or heating). Visible photons of light are emitted and their energy is related to the ionising radiation dose.

Different organs of the body are assigned weighting factors as each has a different sensitivity to radiation damage. The effective dose on the whole body is then a weighted average of the equivalent doses to the different organs of the body.

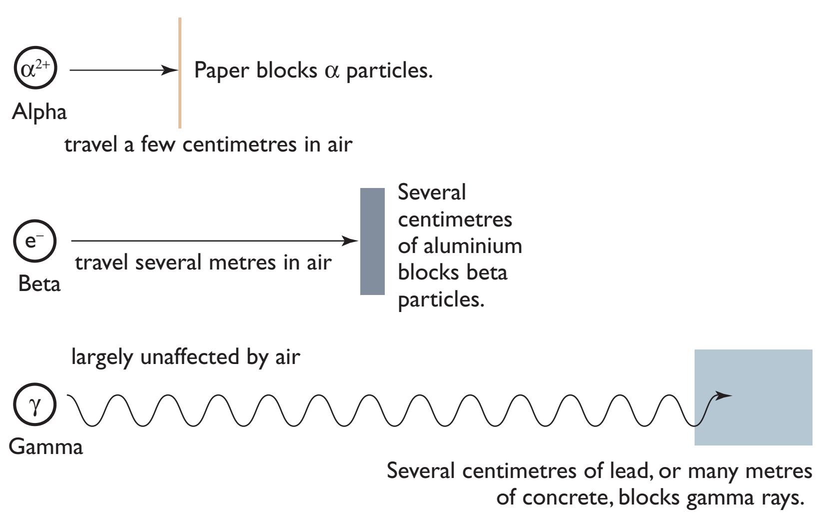


Figure 5.6
Alpha particles have the lowest penetration through matter. Gamma rays have the highest penetration.

TLDs are also produced as finger badges. These small ring-style badges are worn by workers in the nuclear industry to record doses to the hands.

The TLD badges have an open window that allows detection of the shallow radiation dose from beta rays, which will not penetrate the plastic casing. For example, the weak beta rays from carbon-14 and tritium will not penetrate the badge casing.

Geiger–Muller (GM) probe and counter

Nuclear radiation is able to ionise materials. For this reason it is called *ionising radiation*. The GM tube and counter can be used to measure the strength of ionising radiations. Beta radiation is readily detected, although the device can be designed to detect other types of ionising radiation. Figure 5.7 shows the components of this detector.

The radiation enters the GM tube through a mica window at one end. Inside the tube is a low-pressure inert gas such as argon. The high-energy particles cause electrons to be ejected from the neutral atoms.

$$Ar(g) + \text{high energy particle/rays} \rightarrow Ar^{+}(g) + e^{-}$$

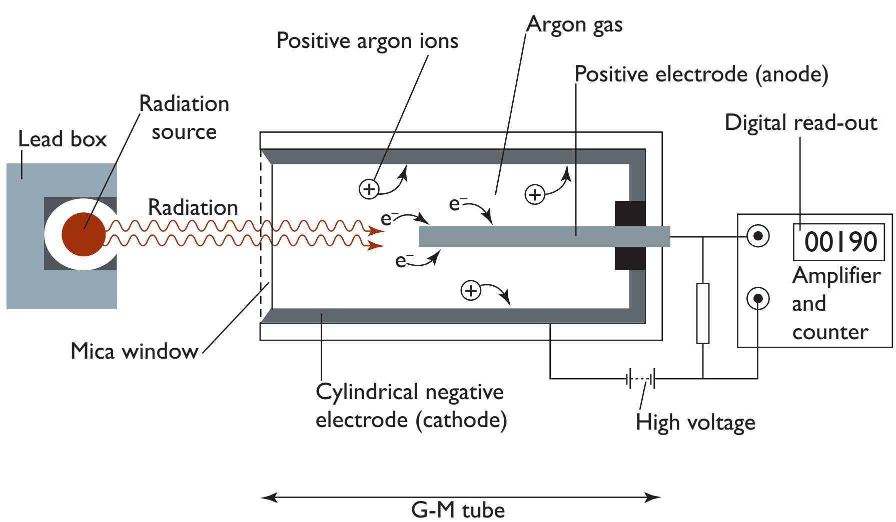


Figure 5.7
The Geiger–Muller (GM) tube detects radiation by the ionisation it causes to the argon gas inside the tube.

Inside the tube is a cylindrical copper cathode and a central positive anode. A high voltage is maintained between these electrodes. The ionisation releases electrons, which are attracted to the anode. As the electrons accelerate due to the high voltage, they cause more ionisations of gaseous atoms, leading to a cascade of electrons that arrive at the anode. An amplified electrical pulse is created at the anode and is detected by the digital counter. The positive ions are attracted to the negative casing and accept electrons to complete the circuit.

Cloud chamber

A cloud chamber contains a cold saturated vapour (e.g. alcohol). A simple cloud chamber can be made by creating a supersaturated alcohol vapour and cooling the container with dry ice. As ionising radiation travels through the air and vapour, it ionises air molecules. The vapour molecules condense onto these ions, and this creates small droplets or cloud trails that reveal the path of the ionising radiation. Alpha particles are strongly ionising but have low penetration. They form thick but short cloud trails.

Beta particles are less ionising but more penetrating, so form thinner, longer trails that may show some zig-zag effects. Gamma rays form very long, wispy trails, as they are very weakly ionising but highly penetrating. Magnetic or electric fields can also be used in conjunction with cloud chambers. In electric and magnetic fields, the positive alpha particles are deflected in different directions from those of negative beta particles. Gamma rays are not deflected.

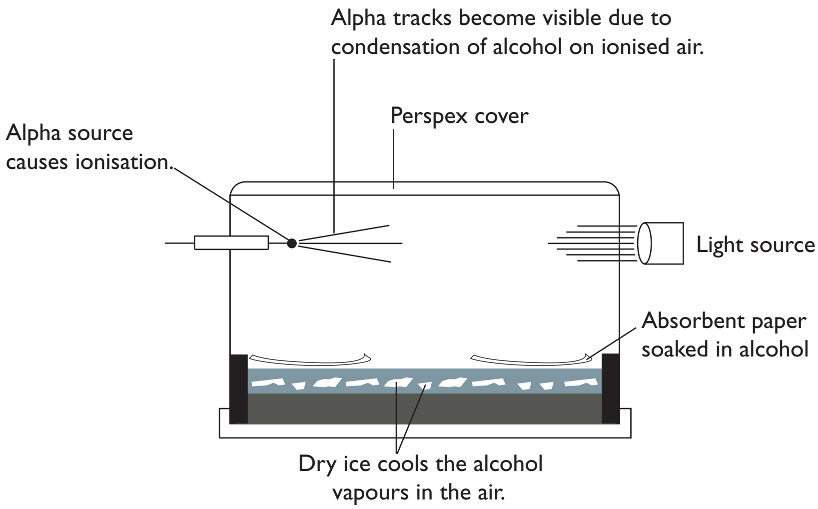


Figure 5.8
The cloud chamber shows the presence of ionising radiation by the cloud trails it produces in the cold supersaturated alcohol vapour.

5.1 Questions

1. Radiation, Q, is emitted from a radioactive source. It had the following properties:
   - Q is stopped by a thin layer of paper.
   - Q is deflected towards the negative electrode in an electric field.
   - Q forms short, thick tracks in a cloud chamber.

   Identify this type of radiation.
2. Radium-226 is an alpha emitter. It decays to form radon gas.
   (a) Identify the atomic number and mass number of radium-226
   (b) Identify the atomic number and mass number of the alpha particle.
   (c) Write the nuclear equation for this decay and determine the mass number of the radon isotope formed.
3. Tritium is a radioactive isotope of hydrogen with a mass number of 3. It is a beta emitter. Predict the mass number and atomic number of the decay product.
4. Meitnerium ($Z = 109$) is a synthetic radioactive element. It decays by alpha emission. Predict the name and atomic number of the element formed following alpha emission.
5. Use the periodic table to determine the element that is formed in each of the following decay processes:
   (a) Sodium-24 undergoes beta decay.
   (b) Lead-210 undergoes alpha decay.
   (c) Arsenic-73 undergoes electron capture.
6. Explain why hassium-265 would be expected to be radioactive.
7. Two of carbon's isotopes are ${}^{12}_{6}C$ and ${}^{14}_{6}C$. Predict which isotope will be stable and which will be radioactive.
8. In nuclear equations, neutrons are represented by the symbol: ${}^{1}_{0}n$.
   When a beryllium-9 nucleus combines with an alpha particle, a neutron is produced. Write a nuclear equation for this reaction and name the other product.

5.2 MAKING AND USING RADIOISOTOPES

Remember

Before beginning this section, you should be able to:

- describe atoms in terms of mass number and atomic number
- distinguish between stable and radioactive isotopes and describe the conditions under which a nucleus is unstable.

Key content

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

- describe how transuranic elements are produced
- describe how commercial radioisotopes are produced
- identify one use of a named radioisotope in industry and in medicine
- describe the way in which the above named industrial and medical radioisotopes are used, and explain their use in terms of their chemical properties
- process information from secondary sources to describe recent discoveries of elements
- use available evidence to analyse benefits and problems associated with the use of radioactive isotopes in identified industries and medicine.

transuranic elements: elements that have an atomic number greater than that of uranium (Z = 92)

Figure 5.9
Glenn Seaborg was involved in the production of nine transuranic elements. He received the Nobel Prize in 1951.

Production of transuranic elements

Elements with atomic numbers greater than 92 have been artificially synthesised over the last sixty years. In 1952 it was suggested that new elements could be discovered in hydrogen bomb test blasts. Thus einsteinium (Z = 99) was discovered on a piece of filter paper flown by an aircraft through the blast zone. Fermium (Z = 100) was identified on a coral reef near an H-bomb test site in the Pacific. In 1982, a few atoms of meitnerium (Z = 109) were produced in Germany's Heavy Ion Research accelerator. This was achieved by the collision of an iron and a bismuth atom. Meitnerium is so unstable that it soon decayed into other radioactive elements.

Neutron bombardment

Neptunium (Z = 93) and plutonium (Z = 94) can be made in nuclear reactors by the neutron bombardment of uranium-238. This was first achieved in 1940 by Glenn Seaborg and his research team.

The unstable U-239 formed decays by beta emission to form neptunium-239 and plutonium-239.

$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \rightarrow ^{239}_{93}\mathrm{Np} + ^{0}_{-1}\mathrm{e}$$

$$^{239}_{93}\mathrm{Np} \rightarrow ^{239}_{94}\mathrm{Pu} + ^{0}_{-1}\mathrm{e}$$

Alpha bombardment

Alpha particles can also be used to produce **transuranic elements**. When plutonium-239 is bombarded with alpha particles an isotope of curium (Z = 96) is formed.

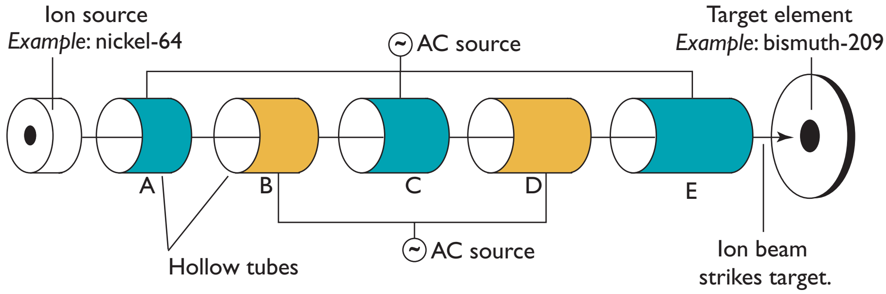
$$^{239}_{94}\mathrm{Pu} + ^{4}_{2}\mathrm{He} \rightarrow ^{242}_{96}\mathrm{Cm} + ^{1}_{0}\mathrm{n}$$

Ion accelerators

The production of transuranic elements with higher atomic numbers is based on the principle of firing accelerated particles into a target. The accelerated particles are usually ions produced in a linear accelerator or heavy ion synchrotron. These ion beams achieve velocities near the speed of light. Nuclear reactions in the target produce unstable nuclei that are detected and analysed. A velocity filter uses electrical and magnetic fields to separate the reaction products and determines their mass.

Roentgenium (Rg, Z = 111) was synthesised in 1994. Nickel-64 ions were accelerated to high energies and directed towards the bismuth-209 target. Roentgenium-272 was formed and a neutron was released. The few atoms of roentgenium that formed rapidly decayed.

$$^{64}_{28}\mathrm{Ni} + ^{209}_{83}\mathrm{Bi} \rightarrow ^{272}_{111}\mathrm{Rg} + ^{1}_{0}\mathrm{n}$$



• When drift tubes A, C and E are negative, tubes B and D are positive.
• The ions accelerate between the tubes, but move at constant speed within the tubes.

Figure 5.10
Linear accelerators are commonly used to produce transuranic elements. The accelerator produces high velocity ions, which are then allowed to collide with the target nucleus.

PRODUCTION OF TRANSURANIC ELEMENT

Only the long-lived transuranic elements have any use. Plutonium is used as a nuclear fission fuel in nuclear power stations. Americium is used in micro-quantities in household smoke detectors.

Production of commercial radioisotopes

In 1919, Ernest Rutherford conducted a series of experiments that led to the discovery of nuclear transmutation. In this famous experiment, nitrogen-14 atoms were converted into oxygen-17 by alpha particle collision.

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

This ground-breaking experiment heralded the age of the production of radioactive isotopes (**radioisotopes**).

Irene and Frederick Joliot-Curie made many discoveries in their investigations into the production of radioisotopes. In 1934 they transmuted aluminium atoms into radioactive phosphorus atoms by alpha particle bombardment. A neutron is emitted during the transmutation. This nuclear reaction can be represented by the equation:

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$

radioisotope: a radioactive isotope of an element; some radioisotopes are natural (e.g. carbon-14) whereas others are synthetic.

'Gentlemen, we have no money, we must think.'
Ernest Rutherford, the Nobel Prize winner for Chemistry in 1908, to a gathering of his assistants when funds to carry out research were low.

The phosphorus-30 atom that is formed is called a radioisotope of natural phosphorus-31. Examination of this nuclear equation reveals that the atomic number and mass number are conserved during this transmutation.

Atomic number (Z)	$13 + 2 = 15 + 0$
Mass number (A)	$27 + 4 = 30 + 1$

Today, radioisotopes are produced using particle accelerators and nuclear reactors. They are used routinely in medicine, industry and research.

High-energy beams of light ions such as protons, deuterons (H-2 ions) as well as He-3 ions and alpha particles are used to generate radioisotopes. Proton beams produce greater yields of radioisotopes due to their penetrating ranges in matter being longer than those of the heavier ions.

The following examples illustrate the production of radioisotopes:

Cobalt-60

Another common method of making radioisotopes is to use neutron bombardment. When pellets of Co-59 are placed inside a nuclear reactor they are bombarded with neutrons. When a neutron is absorbed by the cobalt-59 nucleus an unstable Co-60 nucleus forms. Co-60 is radioactive and begins to decay with the release of beta and gamma radiation.

Tritium (Hydrogen-3)

When Li-6 atoms are bombarded with neutrons an isotope of hydrogen called tritium is formed. Alpha particles are also emitted. The tritium that is formed decays into helium-3 with the loss of a beta particle.

Tritium formation: $$^{6}_{3}Li + ^{1}_{0}n \rightarrow ^{3}_{1}H + ^{4}_{2}He$$

Tritium decay: $$^{3}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{-1}e$$

Technetium-99

Neutrons are excellent projectiles as they have no electric charge and so there is no problem in overcoming electrostatic repulsion with the target nucleus. Molybdenum-98 is an excellent target nucleus. It is converted to Mo-99 by absorption of a neutron. The Mo-99 produced in the reactor is then packaged into a special 'radioisotope generator' kit which can be delivered to hospitals and research laboratories. This generator is used to produce a short-lived radioisotope (e.g. Tc-99m, a gamma-emitter used in medicine, with a **half-life** of 6 hours) on site. The radioisotope is normally released from the generator by dissolving it in 0.9% w/v sodium chloride solution.

half-life: the time taken for the decay of half the atoms of a radioactive element, or for the activity of the sample to decrease by 50%

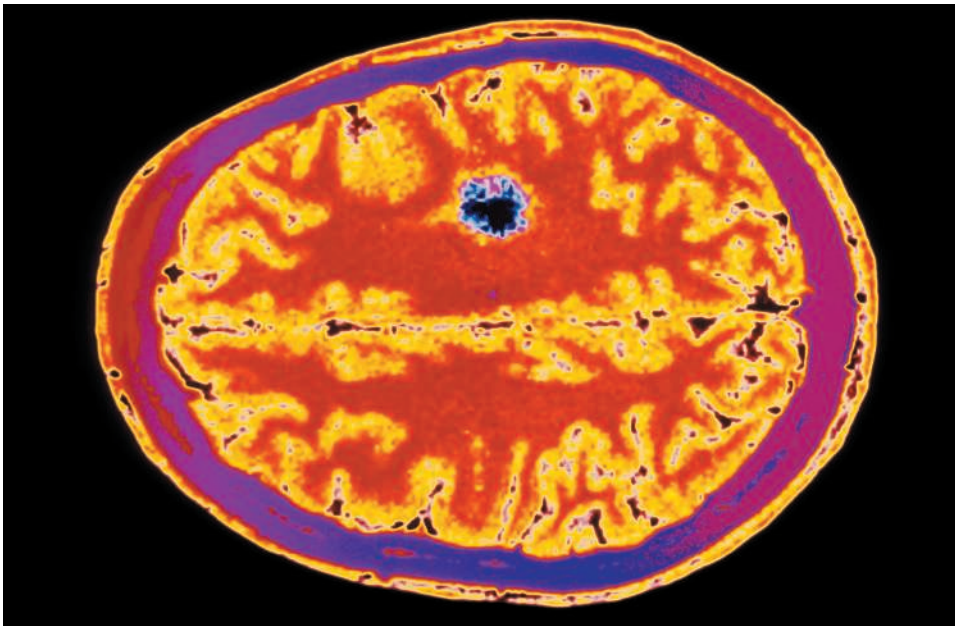


Figure 5.11
Brain tumours can be diagnosed through the use of technetium-99m.

Iodine-123

High velocity protons produced in circular accelerators (cyclotrons or synchrotrons) can be used to produce a useful medical isotope such as iodine-123. The National Medical Cyclotron at the Australian Nuclear Science and Technology Organisation (ANSTO) produces I-123 along with other important medical radioisotopes such as Ga-67 (for the detection of soft tissue tumours), Tl-201 (for detecting heart problems) and F-18 (a positron emitter that is used to diagnose brain disease and the spread of cancers). In the case of I-123, the cyclotron is used to fire protons (hydrogen ions) at a xenon-124 target. Caesium-123 and two neutrons are formed. The caesium-123 decays through xenon-123 to form iodine-123 via positron emission. Positrons have the same mass as an electron but they possess a positive charge. They form when a proton decays into a neutron.

$$^{124}_{54}Xe + ^{1}_{1}p \rightarrow ^{123}_{55}Cs + 2(^{1}_{0}n)$$

$$^{123}_{55}Cs \rightarrow ^{123}_{54}Xe + ^{0}_{1}e^{+}$$

$$^{123}_{54}Xe \rightarrow ^{123}_{53}I + ^{0}_{1}e^{+}$$

Table 5.1 lists the uses of some common radioisotopes used in industry and medicine.

5.1 DATA ANALYSIS
Radioisotopes

Table 5.1 Uses of radioisotopes

Radioisotope	Radiation emitted	Use
plutonium-239	alpha, gamma	energy production in some nuclear power plants
americium-241	alpha, gamma	smoke detectors
cobalt-60 caesium-137	beta, gamma	sterilisation of surgical instruments; food irradiation to prevent spoilage; detecting flaws in metal castings
hydrogen-3	beta	studies of water movement; age of groundwater
technetium-99m	gamma	gamma ray imaging of blood flow disorders; also used to detect disease in organs such as the heart or brain
iodine-123	beta, gamma	detection and treatment of thyroid disease
strontium-90	beta	monitoring the thickness of steel, paper or plastic sheeting
sodium-24	beta, gamma	detecting leaks in underground water or oil pipes

Samarium-153 is a beta emitter that is used in relieving the pain of secondary cancers lodged in the bone.

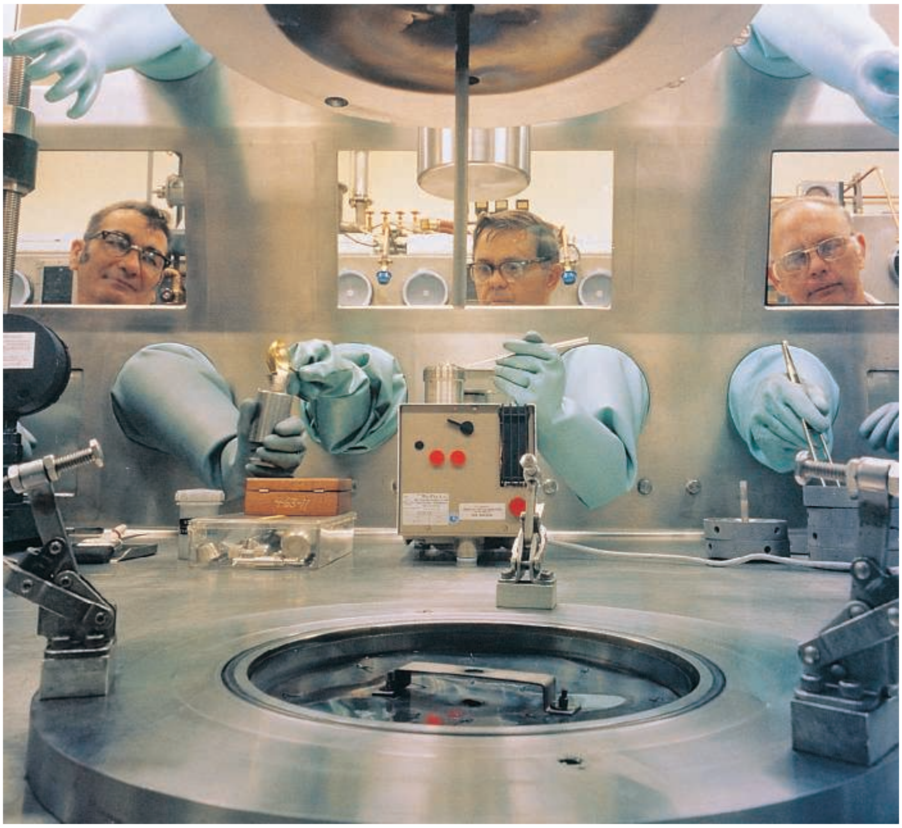


Figure 5.12
Scientists working with highly radioactive material use robotic arms to manipulate materials. The viewing windows are made of special thick glass to protect workers from radiation exposure.

SYLLABUS FOCUS

12. USING INSTRUCTION TERMS CORRECTLY

When answering questions, it is important to know what the instruction terms ('verbs') require you to do. Here is an example:

'Deduce'
This instruction word requires you to draw conclusions from data.

Example:
Deduce the type of radiation, *R*, emitted in the following nuclear equation.

$$^{22}_{11}Na \rightarrow \, ^{22}_{10}Ne + R$$

Answer:
The atomic numbers and mass numbers are conserved. Thus
$A = 22 - 22 = 0$
$Z = 11 - 10 = 1$

Thus R is a positron particle $(^{0}_{1}e^{+})$.

5.2 Questions

1. Deduce the type of radiation released in each of the following.
   (a) Neptunium-239 decays into plutonium-239.
   (b) Uranium-238 decays into thorium-234.
   (c) Plutonium-241 decays into americium-241.
   (d) Nitrogen-13 decays into carbon-13.
2. Describe an example of the production of a radioisotope by:
   (a) neutron bombardment
   (b) alpha bombardment.
3. Roentgenium-272 ($Z = 111$) was synthesised in 1994 when nickel-64 ions collided with a bismuth-209 atom.
   (a) Identify the apparatus used to conduct this experiment.
   (b) Identify the chemical symbol for roentgenium.
   (c) Use a nuclear equation to predict the other product of this nuclear reaction.
4. Cobalt-60 is produced by bombarding Co-59 by neutrons.
   (a) Write a nuclear equation for this reaction.
   (b) Cobalt-60 decays by beta and gamma emission. Write a nuclear equation for the decay of cobalt-60.
   (c) Describe one medical and one industrial use of cobalt-60.
5. Xenon-123 decays to produce iodine-123.
   (a) Write a nuclear equation for this decay and name the radiation emitted.
   (b) Describe how the iodine-123 is used in medical diagnosis.
6. Radioisotopes can be used in scientific research. One such radioisotope is iodine-128 (I-128).

   Consider the following chemical reaction in which iodide ions (I^-) are added to a solution of periodate ions (IO_4^-). The products are shown in the following equation.

   $$2I^- + IO_4^- + H_2O(l) \rightarrow I_2(s) + IO_3^- + 2OH^-$$

   Chemists are interested in whether the iodine solid that forms is derived from the iodide ions or the periodate ions. The radioisotope (I-128) was used to solve this problem.

   Investigation A
   Normal (non-radioactive) periodate ions are allowed to react with radioactive iodide ions. The iodine formed was collected and washed. The sample was found to be radioactive.

   Investigation B
   Normal iodide ions are allowed to react with radioactive periodate ions. No radioactivity was detected in the sample.

   (a) Identify an instrument that could be used to detect radioactivity in the iodine samples.
   (b) The iodine was collected and washed prior to testing for radioactivity. Explain why a chemist would perform this operation.
   (c) Use the information from investigations A and B to identify the source of the iodine atoms in the iodine solid which forms.

7. Americium-241 is used in home smoke detectors. Refer to Figure 5.13 to answer these questions.

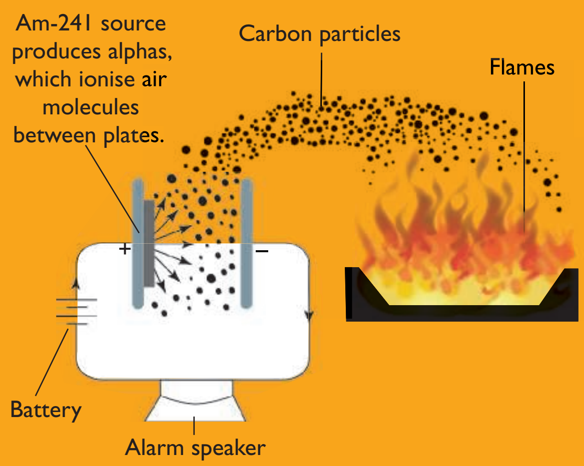


Figure 5.13

   (a) Am-241 is an alpha emitter with a half-life of 432 years. Write a balanced nuclear equation for the decay of americium-241.
   (b) Use the information in the drawing to describe how the smoke detector works.
   (c) Every few years a house owner has to replace the smoke detectors.
      (i) Suggest a reason why smoke detectors fail.
      (ii) Explain why these smoke detectors are safe to handle.

8. Carbon-11 is an important medical radioisotope. It is formed in a medical cyclotron from boron-10.
   (a) Identify the particle that is accelerated by the cyclotron to collide with the boron-10 atoms.
   (b) Explain why the C-11 radioisotope is not manufactured in nuclear laboratories such as Lucas Heights.
   (c) Once the C-11 enters the body of the patient, gamma cameras are used to scan the body. Explain how these gamma rays have been produced.

Weblinks

www.jaconline.com.au/chemnsw/chemistry2

MODULE 1 REVISION

SUMMARY

- Some elements are radioactive. Radioactive atoms have unstable nuclei that decay with the release of particles or rays.
- Light, stable elements have nuclei with an n : p ratio close to 1 : 1. Heavy stable nuclei have n : p ratios close to 1.5 : 1.
- Radioactive elements can decay with the release of alpha particles, beta particles or gamma rays.
- Alpha emission tends to occur in elements with atomic numbers greater than 83. Alpha decay rids a nucleus of excess protons and neutrons.
- Beta emission occurs when the n : p ratio is too high (i.e. a surplus of neutrons).
- When an unstable nucleus has a surplus of protons, stability can be achieved by electron capture.
- Gamma ray emission accompanies many nuclear decays. Gamma emission is a means of shedding excess energy as the nuclear particles rearrange.
- Nuclear decay can be represented by nuclear decay equations.
- Nuclear radiation can be detected using various instruments such as photographic film, thermoluminescent dosimeters, Geiger–Muller counters and cloud chambers.
- Some transuranic elements can be produced by neutron bombardment (e.g. Np, Pu) or alpha bombardment (e.g. Cm).
- Particle accelerators and nuclear reactors can be used to produce new elements and useful radioisotopes.
- Radioisotopes have many practical uses in medicine and industry.

DATA ANALYSIS

5.1 DATA ANALYSIS

RADIOISOTOPES

Process the following information and answer the questions.

Part A: Recent discoveries of radioactive elements

The manufacture of synthetic elements began with Glenn T. Seaborg and his team at Lawrence Berkeley National Laboratory (LBNL) in the late 1940s. He succeeded in synthesising neptunium and plutonium from uranium. Between 1944 and 1953 this team established the existence of americium, curium, berkelium, californium, einsteinium, fermium, mendelevium and nobelium. Element 106 (seaborgium, Sg) has since been named in honour of Glenn Seaborg. The production of even heavier synthetic elements continues to the present time.

Element 114, Uuq (ununquadium) discovered
Theories of nuclear stability had predicted that super-heavy nuclei with atomic numbers around 114 would be more stable than other superheavy elements. In 1999 a research team at Dubna in Russia announced the discovery of element 114. Its half-life was 30 seconds. This is considerably longer than the half-lives of other superheavy nuclei, which are measured in milliseconds. The first isotope of element 114 was created by colliding a calcium-48 ion into a plutonium-244 target using a heavy ion accelerator. Calcium-48 is a rare isotope of calcium, and plutonium is a highly toxic, radioactive metal. A lighter isotope of element-114 was also created by bombarding Pu-242 with Ca-48 ions. Its half-life was 5 seconds.

$$^{244}_{94}\mathrm{Pu} + {}^{48}_{20}\mathrm{Ca} \rightarrow {}^{292}_{114}\mathrm{Uuq}$$

Uuq-292 rapidly lost 4 neutrons, and the resulting isotope decayed by alpha emission to elements of lower atomic number. The first three steps of the decay chain are shown below.

$$^{292}_{114}\mathrm{Uuq} \rightarrow {}^{288}_{114}\mathrm{Uuq} + 4({}^{1}_{0}\mathrm{n})$$

$$^{288}_{114}\mathrm{Uuq} \rightarrow {}^{284}_{112}\mathrm{Uub} + {}^{4}_{2}\mathrm{He}$$

$$^{284}_{112}\mathrm{Uub} \rightarrow {}^{280}_{110}\mathrm{Ds} + {}^{4}_{2}\mathrm{He}$$

Elements 118 and 116 discovered — A case of scientific fraud
In 1999, the LBNL team in California claimed to have produced three atoms of element 118 (Uuo) by bombarding lead targets with an intense beam of high-energy krypton ions in a synchrotron. Element 116 (Uuh) was identified as a decay product. In 2000 the LBNL team announced the discovery of element 116 produced by bombarding curium-248 with calcium-48 ions. In 2001, the Berkeley team withdrew its claim to have discovered elements 118 and 116 in its 1999 experiments, as they could not repeat their discovery in experiments conducted in 2000. As well, other researchers in Japan and Germany could not reproduce their work. In July 2002, Victor Ninov, one of the fifteen LBNL researchers was accused of scientific fraud and misconduct over the analysis of these experiments, and was dismissed. The group's director admitted that sufficient checks on the data and its interpretation were not performed in the rush to announce the discovery. The discovery of element 116 by another independent research group in 2001 may be given priority credit by IUPAC.

Questions

1. Identify the method used by scientists to create superheavy nuclei.
2. Name the elements that were used to create element 114.
3. Use the nuclear equation for the synthesis of element-114 to determine the number of neutrons in the nucleus of the first isotope formed.
4. In what way is the nucleus of element-114 different from those of other superheavy nuclei?
5. Darmstadtium-280 is one of the products of the decay chain of element-114. Predict the atomic number, mass number and name of the next member of the decay chain as alpha emission continues.
6. Explain why the discovery of element-118 (announced in 1999) has been retracted.
7. Is the discovery of element-116 in doubt?

Part B: Issues related to the use of radioactive isotopes

Radioisotopes are widely used in various aspects of chemical research as well as in medicine, industry and agriculture. There are, however, problems associated with the use of radioactive material.

DATA ANALYSIS

Problems in the use of radioisotopes

Some of the problems of using radioisotopes are discussed below.

Radiation dosage

Nuclear radiation is dangerous to living tissue. Continued exposure can lead to disease such as cancer. Scientists and technicians who work with radioactive elements need to minimise their exposure to radiation. Consequently, the radioactive materials are contained in such a way so as to avoid exposure, and the transport of materials within the building or from one location to another is governed by strict safety guidelines. Regular health checks are conducted on those who work with radioisotopes.

When medical radioisotopes are injected into patients, it is important that the radiation dose is minimal. The radioisotope must emit radiation at a low level and not remain long in the body before it is excreted. The radioisotopes that are used in this way should also have a very short half-life. This means that they will rapidly decay into non-radioactive isotopes.

Sometimes the radiation from radioisotopes is used to irradiate and kill cancer cells. The gamma rays from cobalt-60 are used in this way. The rays should be carefully targeted so as not to kill too much healthy tissue surrounding the cancerous tissue. The technicians must also be protected by lead shielding.

Radioactive waste

The products of radioactive decay are often radioactive themselves. This radioactive waste needs to be safely stored for long periods of time (often hundreds or thousands of years). Waste is often stored underground in stable geological structures, as it must not be allowed to contaminate workplaces or the natural environment. ANSTO at Lucas Heights in Sydney has developed a waste storage material called *Synroc*, which immobilises the radioactive waste in a glassy ceramic so that it can be stored safely underground without the danger of leaching by groundwater.

Chemical similarities

For any element, radioactive isotopes have the same chemical properties as the non-radioactive isotopes. There are benefits and problems that arise due to these similarities. One benefit is that radioisotopes can be used as *tracers* to follow the progress of a chemical change in chemical or biochemical systems. Problems arise, however, if the radioisotope enters the body and irradiates the tissues. Thus radioactive iodine-131 is chemically similar to non-radioactive iodine-127. Iodine concentrates in the thyroid gland, and high I-131 levels in thyroid gland could lead to cancer. Due to its short half-life, however, small doses of I-131 can be used safely to diagnose thyroid disease.

Elements in the same periodic group also have similar properties. Strontium and calcium are both members of Group II and have similar chemical properties. Radioactive strontium-90 (a beta emitter) can replace calcium in bone and leukaemia or bone cancer can result.

Important uses of radioisotopes

Let us examine some examples of the use of some radioisotopes.

Iodine-123

Iodine-123 is a short-lived radioisotope. It is a beta and gamma emitter. It is an excellent diagnostic isotope for thyroid studies. It can be ingested by capsule or an oral solution, and it travels through the bloodstream to the thyroid gland where it concentrates. In this manner it is similar to I-131. Iodine-123 releases gamma rays as it decays and these are detected by gamma cameras that create excellent images of the thyroid gland. Its half-life is short (13.2 hours) rather than the 8 days for I-131. It is easier to shield and does not create waste problems. Iodine-123 is also being used in research studies involving Parkinson's disease, schizophrenia and Alzheimer's disease. Iodine-123 can be incorporated into the female hormone estradiol in order to improve breast cancer imaging and screening.

Carbon-11

Positron emission tomography (PET) is an imaging technique that provides doctors with data on the chemistry of the body organs in order to determine whether they are functioning normally or malfunctioning. PET imaging requires cyclotron produced, short-lived radioisotopes that are positron emitters, and which can be incorporated easily into chemical compounds that are the same or similar to other body components. For example, the C-11 radioisotope may be incorporated into a carbon monoxide molecule, which binds strongly to haemoglobin in the blood. The low levels of radioactive C-11 do not cause harm to the body. The 20-minute half-life of C-11 means that the radioisotope must be generated on site in a hospital. The C-11 is produced by proton bombardment of boron-10.

$$^{10}_{5}B + ^{1}_{1}H \rightarrow ^{11}_{6}C$$

The positrons that are emitted inside the body due to the decay of C-11 react with electrons to produce two gamma rays, which are detected by the gamma ray scanner.

Carbon-14

Cabon-14 dating is a technique developed in the 1940's by the Nobel prize-winning chemist Willard Libby. The technique is based on the known rate of beta decay of carbon-14 to produce nitrogen-14. Living things such as plants accumulate carbon-14 in their bodies during their lifetime. This carbon-14 comes originally from the atmosphere where it is formed by collisions of nitrogen-14 with high-energy neutrons from space. While the green plant is alive the C-14 to C-12 ratio remains constant as it is in equilibrium with its environment. On death this equilibrium is not maintained and the carbon-14 slowly decays. Thus the C-14 to C-12 ratio slowly drops. The ratio decreases by half each 5730 years, which it the half-life of carbon-14. By measuring the radioactivity of carbon-based artefacts, their age can be determined.

This technique has been used to investigate the mystery of the Shroud of Turin, which was believed by many to be the burial robe of Jesus Christ. When the flax fibres of the cloth were carbon dated in 1988 they were found to be far less than 2000 years old; in fact, experiments conducted in three separate labs around the world showed the samples of cloth tested to be medieval, and about 700 years old. However, the debate still continues — not because of doubts about the carbon-14 dating technique, but because there are now suggestions that the samples were taken from a section that was repaired in medieval times. Not surprisingly, another investigation using carbon-14 dating is being called for.

The use of carbon-14 dating is restricted to carbon-based artefacts less than 60 000 years old. After this time there is too little carbon-14 remaining to detect.

Strontium-90

Many materials are produced as thin sheeting. Paper, plastics and steel are required in sheets of varying but uniform thickness. The beta particles released by the decay of strontium-90 can be used to monitor the thickness of sheeting as it emerges from the rollers. Figure 5.14 illustrates this use of strontium-90. The Sr-90's long half-life (28 years) means that samples last a long time in industrial sites.

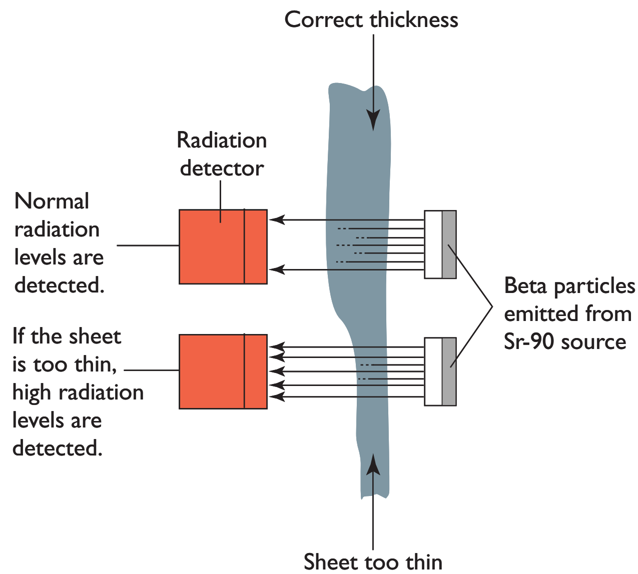


Figure 5.14 Strontium-90 is a beta source. It can be used for thickness gauging.

Beta sources are best as thickness gauges. Alpha rays are not sufficiently penetrating and gamma rays are too penetrating. Changes in the levels of beta rays detected as they pass through the sheeting are automatically monitored.

Questions

1. Identify two problems in working with and handling radioisotopes.
2. Strontium-90 has been observed in radioactive fall-out from nuclear testing in the twentieth century. Explain why such fall-out is a health concern.
3. Explain how carbon-11 is used in PET screening.
4. Explain how strontium-90 is used in thickness gauges.
5. Explain why C-14 can only be used to determine the ages of more recent artefacts.