26 Particle and nuclear physics

Alpha-particle scattering is studied as evidence for the structure of the atom.

Nuclear composition, in terms of nucleons, leads to an appreciation of mass defect and binding energy. Nuclear processes including radioactive decay, fission and fusion are studied.

An introduction to fundamental particles is included.

	Learning outcomes Candidates should be able to:
26.1 Atoms, nuclei and radiation	a) infer from the results of the α-particle scattering experiment the existence and small size of the nucleus b) describe a simple model for the nuclear atom to include protons, neutrons and orbital electrons c) distinguish between nucleon number and proton number d) understand that an element can exist in various isotopic forms, each with a different number of neutrons e) use the usual notation for the representation of nuclides f) appreciate that nucleon number, proton number, and mass-energy are all conserved in nuclear processes g) show an understanding of the nature and properties of α-, β- and γ-radiations (both β^- and β^+ are included) h) state that (electron) antineutrinos and (electron) neutrinos are produced during β^- and β^+ decay
26.2 Fundamental particles	a) appreciate that protons and neutrons are not fundamental particles since they consist of quarks b) describe a simple quark model of hadrons in terms of up, down and strange quarks and their respective antiquarks c) describe protons and neutrons in terms of a simple quark model d) appreciate that there is a weak interaction between quarks, giving rise to β decay e) describe β^- and β^+ decay in terms of a simple quark model f) appreciate that electrons and neutrinos are leptons

26 Particle physics

By the end of this topic, you will be able to:

26.1 (a) infer from the results of the α-particle scattering experiment the existence and small size of the nucleus
(b) describe a simple model for the nuclear atom to include protons, neutrons and orbital electrons
(c) distinguish between nucleon number and proton number
(d) understand that an element can exist in various isotopic forms, each with a different number of neutrons
(e) use the usual notation for the representation of nuclides
(f) appreciate that nucleon number, proton number and mass-energy are all conserved in nuclear processes
(g) show an understanding of the nature and properties of α-, β- and γ-radiations (both β^- and β^+ are included)
(h) state that (electron) antineutrinos and (electron) neutrinos are produced during β^- and β^+ decay

26.2 (a) appreciate that protons and neutrons are not fundamental particles since they contain quarks
(b) describe a simple quark model of hadrons in terms of up, down and strange quarks and their respective antiquarks
(c) describe protons and neutrons in terms of a simple quark model
(d) appreciate that there is a weak interaction between quarks, giving rise to β decay
(e) describe β^- and β^+ decay in terms of a simple quark model
(f) appreciate that electrons and neutrinos are leptons

Starting points

- The atom consists of a very small nucleus containing protons and neutrons, surrounded by orbiting electrons.
- The decay of unstable nuclei leads to emissions.
- Appreciate that protons and neutrons are not fundamental particles.

26.1 Atomic structure and radioactivity

The atoms of all elements are made up of three particles called **protons**, **neutrons**, and **electrons**. The protons and neutrons are at the centre or nucleus of the atom. The electrons orbit the nucleus.

We shall see later that the diameter of the nucleus is only about 1/10000 of the diameter of an atom.

Figure 26.1 illustrates very simple models of a helium atom and a lithium atom.

The protons and neutrons both have a mass of about one atomic mass unit u ($1\,u = 1.66 \times 10^{-27}\,kg$). The atomic mass unit is defined and used in the A level course in Topic 10. By comparison, the mass of an electron is very small, about 1/2000 of 1 u. The vast majority of the mass of the atom is therefore in the nucleus.

The basic properties of the proton, neutron and electron are summarised in Table 26.1.

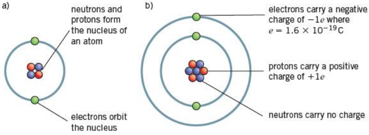

Figure 26.1 Structures of a) a helium atom and b) a lithium atom

Table 26.1

	approximate mass	charge	position
proton	u	$+e$	in nucleus
neutron	u	0	in nucleus
electron	u/2000	$-e$	orbiting nucleus

Atoms and ions

Atoms are uncharged because they contain equal numbers of protons and electrons and the charge on an electron is equal and opposite to the charge on a proton. If an atom loses one or more electrons, so that it does not contain an equal number of protons and electrons, it becomes charged and is called an **ion**.

For example, if a sodium atom loses one of its electrons, it becomes a positive sodium ion.

$$\underset{\text{sodium atom}}{\text{Na}} \rightarrow \underset{\text{sodium ion}}{\text{Na}^+} + \underset{\text{electron}}{\text{e}^-}$$

If an atom gains an electron, it becomes a negative ion.

Proton number and nucleon number

The number of protons in the nucleus of an atom is called the **proton number** (or **atomic number**) Z.

The number of protons together with the number of neutrons in the nucleus is called the **nucleon number** (or **mass number**) A.

A **nucleon** is the name given to either a proton or a neutron in the nucleus.

The difference between the nucleon number (A) and the proton number (Z) gives the number of neutrons in the nucleus.

Representation of nuclides

If the chemical symbol of an element is X, a particular atom of this element, a nuclide, is represented by the notation

$$^{\text{nucleon number}}_{\text{proton number}}\text{X} = {}^{A}_{Z}\text{X}.$$

The element changes for every Z number and the symbol X changes. A nuclide is the name given to a class of atoms whose nuclei contain a specified number of protons and a specified number of neutrons. The nucleus of one form of sodium contains 11 protons and 12 neutrons. Therefore its proton number Z is 11 and the nucleon number A is 11 + 12 = 23. This nuclide can be shown as ${}^{23}_{11}$Na. All atoms with nuclei that contain 11 protons and 12 neutrons belong to this class and are the same nuclide.

Nuclides with nuclei that have the same atomic number Z but a different mass number are **isotopes** of the same element.

Example

An oxygen nucleus is represented by $^{16}_{8}O$. Describe its atomic structure.

The nucleus has a proton number of 8 and a nucleon number of 16. Thus, its nucleus contains **8 protons** and 16 − 8 = **8 neutrons**. There are also **8 electrons** (equal to the number of protons) orbiting the nucleus.

Now it's your turn

1 Write down the proton number and the nucleon number for the potassium nucleus $^{40}_{19}K$. Deduce the number of neutrons in the nucleus.

Isotopes

Sometimes atoms of the same element have different numbers of neutrons in their nuclei. The most abundant form of chlorine contains 17 protons and 18 neutrons in its nucleus, giving it a nucleon number of 17 + 18 = 35. This is often called chlorine-35. Another form of chlorine contains 17 protons and 20 neutrons in the nucleus, giving it a nucleon number of 37. This is chlorine-37. Chlorine-35 and chlorine-37 are said to be **isotopes** of chlorine.

Isotopes are different forms of the same element which have the same number of protons but different numbers of neutrons in their nuclei.

Some elements have many isotopes, but others have very few. For hydrogen, the most common isotope is hydrogen-1. Its nucleus is a single proton. Hydrogen-2 is called deuterium; its nucleus contains one proton and one neutron. Hydrogen-3, with one proton and two neutrons, is called tritium.

Note that the term isotope is also used to describe nuclei with the same proton number (that is, nuclei of the same element) but with different nucleon numbers. You may also come across the term **nuclide**.

A nuclide is one type of nucleus with a particular nucleon number and a particular proton number.

α-particles, β-particles and γ-radiation

Some elements have nuclei which are unstable. That is, the combination of protons and neutrons in the nucleus is such that the forces acting on the nucleons do not balance. In order to become more stable, they emit particles and/or electromagnetic radiation. The nuclei are said to be **radioactive**, and the emission is called **radioactivity**. The emissions are invisible to the eye, but their tracks were first made visible in a device called a cloud chamber. The photograph in Figure 26.2 shows tracks created by one type of emission, α-particles.

Investigations of the nature and properties of the emitted particles or radiation show that there are three different types of emission. The three types are α-particles (alpha-particles), β-particles (beta-particles) and γ-radiation (gamma radiation). All three emissions originate from the nucleus.

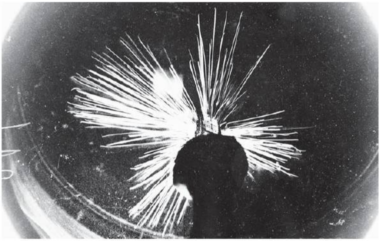

Figure 26.2 Tracks of α-particles

α-particles

Like a helium nucleus, an α-particle contains two protons and two neutrons and, hence, carries a charge of $+2e$. α-particles travel at speeds of up to about $10^7\,\mathrm{m\,s^{-1}}$ (about 5% of the speed of light). α-particle emission is the least penetrating of the three types of emission. It can pass through very thin paper, but is unable to penetrate thin card. Its range in air is a few centimetres. Because α-particles are charged, they can be deflected by electric and magnetic fields.

An α-particle is identical to the nucleus of a helium atom.

In terms of symbols:

An α-particle is written as ${}^{4}_{2}\mathrm{He}$.

As α-particles travel through matter, they interact with nearby atoms causing them to lose one or more electrons. The ionised atom and the dislodged electron are called an ion pair. The production of an ion pair requires the separation of unlike charges, and this process requires energy. α-particles have a relatively large mass and charge, and consequently they are efficient ionisers. They may produce as many as 10^5 ion pairs for every centimetre of air through which they travel. Thus, they lose energy relatively quickly, and have low penetrating power.

When the nucleus of an atom emits an α-particle, it is said to undergo α-decay. The nucleus loses two protons and two neutrons in this emission.

In α-decay, the proton number of the nucleus decreases by two, and the nucleon number decreases by four.

Each element has a particular proton number, and therefore α-decay causes one element to change into another. (This process is sometimes called **transmutation**.) The original nuclide is called the **parent nuclide**, and the new one the **daughter nuclide**.

For example, uranium-234 (the parent nuclide) may emit an α-particle. The daughter nuclide is thorium-230. In addition, energy is released. This emission is represented by the nuclear equation

$${}^{234}_{92}\mathrm{U} \rightarrow {}^{230}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} + \text{energy}$$

The atomic mass of the decay products is less than the mass of the parent nuclide (${}^{234}_{92}\mathrm{U}$). The energy equivalent of the difference in the mass appears as kinetic energy of the α-particle and the recoiling daughter nuclide (${}^{230}_{90}\mathrm{Th}$) and a γ-photon. Therefore, mass–energy is conserved. Linear momentum is also conserved in this type of nuclear reaction. The same amount of energy is released in the decay of each nucleus of $^{234}_{92}U$. The α-particles emitted from a particular radioactive nuclide have the same kinetic energy.

β-particles

A radioactive nucleus that decays by β decay may emit a negative (β^-) or positive (β^+) electron. The positive electron (β^+) is also known as a positron or an antielectron ($\bar{e}$).

β-particles are fast moving electrons, β^-, or positrons, β^+.

β-particles have speeds in excess of 99% of the speed of light. These particles have half the charge and very much less mass than α-particles. Consequently, they are much less efficient than α-particles in producing ion pairs. They are, thus, far more penetrating than α-particles, being able to travel up to about a metre in air. They can penetrate card and sheets of aluminium up to a few millimetres thick. Their charge means that they are affected by electric and magnetic fields. However, there are important differences between the behaviour of α- and β-particles in these fields. β-particles may carry negative charge or positive charge, and thus may be deflected in the same direction or opposite direction to the positively charged α-particles. β-particles experience a much larger deflection when moving at the same speed as α-particles, because the mass of a β-particle is much less than that of an α-particle.

A β^- particle may be emitted from a lead-214 nucleus (the parent nuclide). The daughter nuclide is bismuth-214 and, in addition, energy is released. The emission is represented by the nuclear equation

$$^{214}_{82}Pb \rightarrow {}^{214}_{83}Bi + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu} + \text{energy}$$

A β^+ particle may be emitted from a phosphorus-30 nucleus (the parent nuclide). The daughter nuclide is silicon-30 and energy is also released. The emission is represented by the nuclear equation:

$$^{30}_{15}P \rightarrow {}^{30}_{14}Si + {}^{0}_{1}e + {}^{0}_{0}\nu + \text{energy}$$

The symbols ${}^{0}_{0}\nu$ and ${}^{0}_{0}\bar{\nu}$ represent a neutrino and an antineutrino respectively. These particles have no electrical charge and little or no mass and are emitted from the nucleus at the same time as the β-particle.

It was stated on page 168 that the nucleus contains protons and neutrons. What, then, is the origin of β-particle emission? Each β-particle certainly comes from a nucleus, not from the electrons outside the nucleus. The process for this type of decay is that, just prior to β^- emission, a neutron in the nucleus forms a proton, a negative electron and an antineutrino. The ratio of protons to neutrons in the nucleus is changed and this makes the daughter nucleus more stable.

In fact, *free* neutrons are known to decay as follows:

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu} + \text{energy}$$

A similar process happens in the nucleus. In β^- decay, a negative electron and antineutrino $\bar{\nu}$ are emitted from the nucleus. This leaves the nucleus with the same number of nucleons as before, but with one extra proton and one fewer neutron.

In β^+ emission, a proton in the nucleus forms a neutron, a positive electron and a neutrino. This process again changes the ratio of protons to neutrons in the nucleus and makes the daughter nucleus more stable.

In β^+ decay the proton is considered to transform itself as follows:

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e + {}^{0}_{0}\nu + \text{energy}$$

In β^+ decay, the positive electron and a neutrino are emitted from the nucleus. This leaves the nucleus with the same number of nucleons as before, but with one extra neutron and one fewer proton.

In β^- decay (negative electron), a daughter nuclide is formed with the proton number increased by one, but with the same nucleon number.

In β^+ decay (positive electron), a daughter nuclide is formed with the proton number decreased by one, but with the same nucleon number.

The antimatter particle, the positive electron, very quickly meets its equivalent matter particle, the negative electron. The two particles annihilate each other to produce γ-radiation. This makes the positive electron difficult to detect.

The atomic mass of the decay products is less than the mass of the parent nucleus. The energy equivalent of the difference in the mass is shared between the kinetic energy of the β-particle and the recoiling daughter nucleus and the energy of the neutrino or antineutrino. Therefore mass–energy is conserved. The same amount of energy is released in the decay of each particular parent nucleus. However, the electrons emitted from a particular radioactive nuclide have varying amounts of kinetic energy. The amount depends on the way the total energy available is shared between the electron and the neutrino. The sum of the electron's energy and the neutrino's energy is constant for the decay of a particular nuclide.

Kinetic energy of the subatomic particles

The SI unit of energy is the joule. The energies in nuclear reactions are very small compared to the joule. A more convenient unit to use is the electron-volt (eV). This is the work done (energy gained) by an electron when accelerated through a potential difference of one volt. Since work done equals potential difference × charge, one eV is equivalent to 1.602×10^{-19} J. One mega electron-volt (MeV) is 10^6 eV or 1.602×10^{-13} J.

Examples

1 A strontium-90 atom (the parent nuclide) may decay with the emission of a β-particle to form the daughter nuclide yttrium-90. The decay is represented by the nuclear equation

$$^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + \beta + x + \text{energy}$$

State and explain whether the β-particle is a negative or positive electron. State the type of particle represented by x.

The proton number has increased by one, hence a **negative electron** is emitted. The x is an **antineutrino** as this particle is emitted with a negative electron.

2 Calculate the energy in joules of 1 GeV.

potential difference = energy transformed / charge

energy = 10^9 (V) × charge on electron (e) = 1.6×10^{-10} J

Hence 1 GeV = $\mathbf{1.6 \times 10^{-10}}$ **J**

Now it's your turn

2 The mass of strontium-90 in the example above does not equal the total mass of particles formed after the reaction. Explain why mass seems not to be conserved.

3 The energy released in the example above is 3.6 MeV. Calculate the energy in joules.

γ-radiation

γ-radiation is part of the electromagnetic spectrum with wavelengths between 10^{-11} m and 10^{-13} m.

Since γ-radiation has no charge, its ionising power is much less than that of either α- or β-particles. γ-radiation penetrates almost unlimited thicknesses of air, several metres of concrete or several centimetres of lead.

α- and β-particles are emitted by unstable nuclei which have excess energy. The emission of these particles results in changes in the ratio of protons to neutrons, but the nuclei may still have excess energy. The nucleus may return to its unexcited (or ground) state by emitting energy in the form of γ-radiation.

In γ-emission, no particles are emitted and there is, therefore, no change to the proton number or nucleon number of the parent nuclide.

For example, when uranium-238 decays by emitting an α-particle, the resulting nucleus of thorium-234 contains excess energy (it is in an excited state) and emits a photon of γ-radiation to return to the ground state. This process is represented by the nuclear equation

$$^{234}_{90}\text{Th}^* \rightarrow {}^{234}_{90}\text{Th} + \gamma$$

The * next to the symbol Th on the left-hand side of the equation shows that the thorium nucleus is in an excited state.

Note that in all radioactive decay processes (and, in fact, in all processes of nuclear reactions) nucleon number and proton number are conserved. Hence, for all equations representing nuclear reactions, the sum of the numbers at the top of the symbols on the left-hand side of the equation (the sum of the nucleon numbers) is equal to the sum of the nucleon numbers on the right-hand side. Similarly, the sum of the numbers at the bottom of the symbols on the left-hand side (the sum of the proton numbers) is equal to the sum of the proton numbers on the right-hand side. Energy and mass, taken together, are also conserved in all nuclear processes.

Summary of the properties of radioactive emissions

Table 26.2 summarises the properties of α-particles, β-particles and γ-radiation.

Table 26.2

property	α-particle	β-particle	γ-radiation
mass	4 u	about u/2000	0
charge	$+2e$	$-e$ or $+e$	0
nature	helium nucleus (2 protons + 2 neutrons)	negative or positive electron	short-wavelength electromagnetic waves
speed	up to 0.05c	more than 0.99c	c
penetrating power	few cm of air	few mm of aluminium	few cm of lead
relative ionising power	10^4	10^2	1
affects photographic film?	yes	yes	yes
deflected by electric, magnetic fields?	yes, see Figure 26.3	yes, see Figure 26.3	no

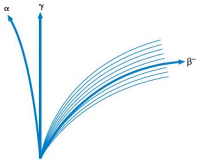

Figure 26.3 Deflection of α- and β⁻-particles and γ-radiation by a magnetic field into the page

Figure 26.3 illustrates a hypothetical demonstration of the effect of a magnetic field on α, β⁻ and γ emissions. The direction of the magnetic field is perpendicularly into the page. γ-radiation is uncharged, and is not deflected by the magnetic field. Because α- and β⁻-particles have opposite charges, they are deflected in opposite directions. Note that the deviation of α-particles is, in general, much less than that of β-particles and the relative deflections are not shown to scale. The α-particles from a particular nuclide all deviate by the same amount. The β-particles from a particular nuclide, by contrast, have a range of deflections indicating that they have a range of energies. Deflections can be observed with an electric field. (Make sure that you can confirm that an electric field should be in the plane of the paper and with a direction horizontal and to the left in order to obtain the deflections in the same direction as those obtained with the magnetic field.) Note, β⁺-particles would be deflected in the same direction as the α-particles, with a similar pattern to that of the β⁻-particles.

Radioactive decay series

The daughter nuclide of a radioactive decay may, itself, be unstable and so may emit radiation to give another different nuclide. This sequence of radioactive decay from parent nuclide through succeeding daughter nuclides is called a **radioactive decay series**. The series ends when a stable nuclide is reached.

Table 26.3 Part of the decay series of uranium-238

decay	radiation emitted
$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He + \gamma$	α, γ
$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ^{0}_{-1}e + \gamma$	β^-, γ
$^{334}_{91}Pa \rightarrow ^{234}_{92}U + ^{0}_{-1}e + \gamma$	β^-, γ
$^{234}_{92}U \rightarrow ^{230}_{90}Th + ^{4}_{2}He + \gamma$	α, γ
$^{230}_{90}Th \rightarrow ^{226}_{88}Ra + ^{4}_{2}He + \gamma$	α, γ
$^{226}_{88}Ra \rightarrow ^{226}_{86}Rn + ^{4}_{2}He$	α
$^{222}_{86}Rn \rightarrow ^{218}_{84}Po + ^{4}_{2}He$	α

Part of such a radioactive decay series, the uranium series, is shown in Table 26.3.

Detecting radioactivity

Some of the methods used to detect radioactive emissions are based on the ionising properties of the particles or radiation.

The Geiger counter

Figure 26.4 illustrates a Geiger-Müller tube with a scaler connected to it. When radiation enters the window, it creates ion pairs in the gas in the tube. These charged particles, and particularly the electrons, are accelerated by the potential difference between the central wire anode and the cylindrical cathode. These accelerated particles then cause further ionisation. The result of this continuous process is described as an **avalanche effect**. That is, the entry of one particle into the tube and the production of one ion pair results in very large numbers of electrons and ions arriving at the anode and cathode respectively. This gives a pulse of charge which is amplified and counted by the scaler or ratemeter. (A scaler measures the total count of pulses in the tube during the time that the scaler is operating. A ratemeter continuously monitors the number of counts per second.) Once the pulse has been registered, the charges are removed from the gas in readiness for further radiation entering the tube.

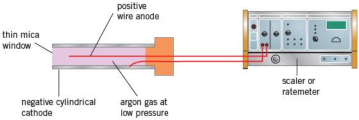

Figure 26.4 Geiger-Müller tube and scaler

Figure 26.5 Film badge dosimeter

Photographic plates

When a radioactive emission strikes a photographic film, the film reacts as if it had been exposed to a small amount of visible light. When the film is developed, fogging or blackening is seen. This fogging can be used to detect, not only the presence of radioactivity, but also the dose of the radiation.

Figure 26.5 shows a film badge dosimeter. It contains a piece of photographic film which becomes fogged when exposed to radiation. Workers who are at risk from radiation wear such badges to gauge the type and dose of radiation to which they have been exposed. The radiation passes through different filters before reaching the film. Consequently, the type of radiation, as well as the quantity, can be assessed.

The scintillation counter

Early workers with radioactive materials used glass screens coated with zinc sulfide to detect radiation. When radiation is incident on the zinc sulfide, it emits a tiny pulse of light called a **scintillation**. The rate at which these pulses are emitted indicates the intensity of the radiation.

The early researchers worked in darkened rooms, observing the zinc sulfide screen by eye through a microscope and counting the number of flashes of light occurring in a certain time. Now a scintillation counter is used (Figure 26.6).

Often a scintillator crystal is used instead of a zinc sulfide screen. The crystal is mounted close to a device known as a photomultiplier, a vacuum-tube device which uses the principle of photoelectric emission (see Topic 25). Flashes of light cause the emission of photoelectrons from the negative electrode of the photomultiplier. The photoelectric current is amplified inside the tube. The output electrode is connected to a scaler or ratemeter, as with the Geiger-Müller tube.

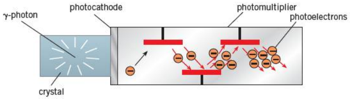

Figure 26.6 Scintillation counter

Background radiation

Radioactivity is a natural phenomenon. Rocks such as granite contain small amounts of radioactive nuclides, some foods we eat emit radiation, and even our bodies are naturally radioactive. Although the atmosphere provides life on Earth with some shielding, there is, nevertheless, some radiation from outer space (cosmic radiation). In addition to this natural radioactivity, we are exposed to radiation from man-made sources. These are found in medicine, in fallout from nuclear explosions, and in leaks from nuclear power stations. The sum of all this radiation is known as **background radiation**. Figure 26.7 indicates the relative proportions of background radiation coming from various sources.

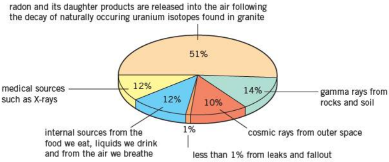

Figure 26.7 Sources of background radiation

In carrying out experiments with radioactive sources, it is important to take account of background radiation. In order to determine the count-rate due to the radioactive source, the background count-rate must be subtracted from the total measured count-rate. Allowance for background radiation gives the corrected count-rate.

The spontaneous and random nature of radioactive decay

Detection of the count-rate of radioactive sources shows that the emission of radiation is both *spontaneous* and *random*. It is a spontaneous process because it is not affected by any external factors, such as temperature or pressure. Decay is random in that it is not possible to predict which nucleus in a sample will decay next. There is, however, a constant probability (or chance) that a nucleus will decay in any fixed period of time. We will look at this in more detail in the A level course Topic 26.

Probing matter

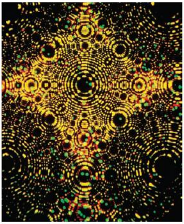

Figure 26.8 Ion microscope photograph of iridium

Figure 26.8 shows a photograph taken with an ion microscope, a device which makes use of the de Broglie wavelength of gas ions (see Topic 25). It shows a sample of iridium at a magnification of about five million. The positions of individual iridium atoms can be seen.

Photographs like this reinforce the idea that all matter is made of very small particles that we call atoms. Advances in science at the end of the nineteenth and the beginning of the twentieth century led most physicists to believe that atoms themselves are made from even smaller particles, some of which have positive or negative charges. Unfortunately, even the most powerful microscopes cannot show us the internal structure of the atom. Many theories were put forward about the structure of the atom, but it was a series of experiments carried out by Ernest Rutherford and his colleagues around 1910 that led to the birth of the model we now know as the **nuclear atom**.

Probing matter using α-particles

In 1911, Rutherford and two of his associates, Geiger and Marsden, fired a beam of α-particles at a very thin piece of gold foil. A zinc sulfide detector was moved around the foil to detect the directions in which the α-particles travelled after striking the foil (Figure 26.9).

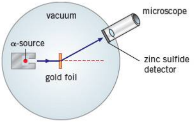

Figure 26.9 α-scattering experiment

They discovered that:
- the vast majority of the α-particles passed through the foil with very little or no deviation from their original path
- a small number of particles were deviated through an angle of more than about 10°
- an extremely small number of particles (one in ten thousand) were deflected through an angle greater than 90°.

From these observations, the following conclusions could be drawn.

- The majority of the mass of an atom is concentrated in a very small volume at the centre of the atom. Most α-particles would, therefore, pass through the foil undeviated.
- The centre (or nucleus) of an atom is charged. α-particles, which are also charged, passing close to the nucleus will experience a repulsive force causing them to deviate.
- Only α-particles that pass very close to the nucleus, almost striking it head-on, will experience large enough repulsive forces to cause them to deviate through angles greater than 90°. The fact that so few particles did so confirms that the nucleus is very small, and that most of the atom is empty space.

Figure 26.10 shows some of the possible trajectories of the α-particles. Using the nuclear model of the atom and equations to describe the force between charged particles, Rutherford calculated the fraction of α-particles that he would expect to be deviated through various angles. The calculations agreed with the results from the experiment. This confirmed the nuclear model of the atom. Rutherford calculated that the diameter of the nucleus is about 10^{-15} m, and the diameter of the whole atom about 10^{-10} m. Figure 26.11 shows the features of the nuclear model of a nitrogen atom.

Some years later, the α-particle scattering experiment was repeated using α-particles with higher energies. Some discrepancies between the experimental results and Rutherford's scattering formula were observed. These seemed to be occurring because the high-energy α-particles were passing very close to the nucleus, and were experiencing, not only the repulsive electrostatic force, but also a strong attractive force which appears to act over only a very short range. This became known as the **strong nuclear force**. This is the force that holds the nucleus together.

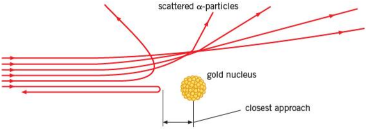

Figure 26.10

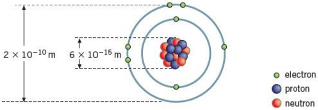

Figure 26.11 The diameter of a nitrogen atom is more than 30 000 times bigger than the diameter of its nucleus.

Probing matter using electrons

Electrons are not affected by the strong nuclear force. It was suggested that they might, therefore, be a more effective tool with which to investigate the structure of the atom. The A level course in Topic 25 shows that moving electrons have a wave-like property, and can be diffracted.

If a beam of electrons is directed at a sample of powdered crystal and the electron wavelength is comparable with the interatomic spacing in the crystal, the electron waves are scattered from planes of atoms in the tiny crystals, creating a diffraction pattern (Figure 26.12). The fact that a diffraction pattern is obtained confirms the regular arrangement of the atoms in a crystalline solid. Measurements of the angles at which strong scattering is obtained can be used to calculate the distances between planes of atoms.

If the energy of the electron beam is increased, the wavelength decreases. Eventually, the electron wavelength may be of the same order of magnitude as the diameter of the nucleus. Probing the nucleus with high-energy electrons, rather than α-particles, gives a further insight into the dimensions of the nucleus, and also gives information about the distribution of charge in the nucleus itself.

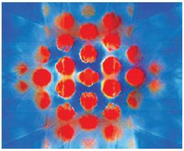

Figure 26.12 Electron diffraction pattern of a sample of pure titanium

26.2 Fundamental particles

In the nineteenth century, the atom was considered to be the fundamental particle from which all matter was composed. This idea was used to explain the basic structure of all elements. Experiments performed at the end of the nineteenth century and beginning of the twentieth century provided evidence for the structure of an atom. The conclusions were that all atoms have a nucleus containing protons which is surrounded by electrons and that the nucleus was very small compared with the size of the atom. The neutron was introduced to explain the discrepancy between the mass of the atom and the mass from the number of protons (number of positive charges). In 1932 Chadwick discovered the neutron and the fundamental particles were then considered to be the proton, the neutron and the electron. The structure of the atom was then considered to be similar to that shown in Figure 26.1.

The particles in an atom must experience forces in order to maintain its structure. The forces were the gravitational force that acts between all masses (see Topic 8) and the electrostatic force that acts between charged objects (see Topic 17). The electrostatic force of repulsion is approximately 10^{36} times greater than the gravitational force of attraction between protons. Another attractive force must keep the protons together in the nucleus. This force is known as the **strong force** and acts between nucleons. The force does not seem to have any effect outside the nucleus and is, therefore, considered to be very short range (a little more than the diameter of nuclei, 10^{-14} m). There appears to be a limiting spacing between nucleons which is similar in different nuclei and this suggests that the force is repulsive as soon as the nucleons come close together. The strong force does not act on electrons.

The strong force acts on protons and neutrons but **not** on electrons.

Example

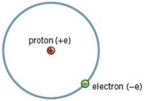

Figure 26.13 Hydrogen atom

Figure 26.13 illustrates a hydrogen atom with an electron orbiting the nucleus.

(a) State, for the forces acting on the electron and the proton,
- **(i)** their nature,
- **(ii)** their direction.

(b) Explain why a strong force does not act on the electron or proton.

(a)
- **(i)** gravitational force (due to the mass of the electron and proton), electrostatic force (due to the charge on the electron and proton)
- **(ii)** both forces are attractive and, therefore, directed from the one particle towards the other particle.

(b) The electron is not a nucleon and, hence, is not affected by the strong force. There is only one nucleon and the strong force acts between nucleons.

Now it's your turn

4 State the forces acting on the nucleons of a helium nucleus.

Hadrons and leptons

The discovery of antimatter in cosmic radiation supported the theory developed from the special theory of relativity and quantum theory that all fundamental particles have a corresponding antimatter particle. The matter and antimatter particles have the same mass but opposite charge. The following particles were required to support the theory: the antiproton, the antineutron and the antielectron. The symbols used for the antiparticle are $\bar{p}$ for the antiproton, $\bar{n}$ for the antineutron and $\bar{e}$ for the antielectron.

The antielectron or positive electron was introduced in β-particle decay on page 172. It is also known as the positron.

Many other particles were discovered in cosmic radiation throughout the twentieth century, giving support for the idea that the electron, proton and neutron were not the only fundamental particles.

The numerous types of particles are placed into two main categories. Those affected by the strong force are called **hadrons**, for example protons and neutrons, and those not affected by the strong force are called **leptons**, for example electrons and positrons.

The many different particles discovered in cosmic radiation have been reproduced in high-energy collisions using accelerators such as those at Stanford in California and CERN in Switzerland during the second half of the twentieth century. A vast number of collisions were carried out and a large number of hadrons were produced. Two of the conclusions to these reactions were:

- the total electrical charge remains constant
- the total number of nucleons normally remains constant.

The quark model of hadrons

The problem of what were considered to be fundamental particles was resolved by the quark model for hadrons. In this model, the hadrons are made up of three smaller particles called **quarks**. The types of quark, called flavours of quark, are **up** (**u**), **down** (**d**) and **strange** (**s**). The quark flavours have charge and strangeness as shown in Table 26.4.

Table 26.4 Charge and strangeness values for the three quarks

flavour	charge	strangeness
up (u)	$+\frac{2}{3}$	0
down (d)	$-\frac{1}{3}$	0
strange (s)	$-\frac{1}{3}$	−1

There are three **antiquarks**, $\bar{u}$, $\bar{d}$ and $\bar{s}$: these have the opposite values of charge and strangeness.

Protons and neutrons consist of three quarks.

proton:		u	u	d	**neutron**:		u	d	d
charge	+1	$+\frac{2}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	charge	0	$+\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
strangeness	0	0	0	0	strangeness	0	0	0	0

In strong interactions, the quark flavour is conserved.

Example

State the values of charge and strangeness for the antiquarks $\bar{u}$, and $\bar{d}$

$\bar{u}$ charge $-\frac{2}{3}$ strangeness 0

and $\bar{d}$ charge $+\frac{1}{3}$ strangeness 0

Now it's your turn

5 Show whether the following reaction can occur.

$$p + p \rightarrow p + \bar{p} + n$$

Leptons

Leptons are particles that are not affected by the strong force. The electron and neutrino and their antimatter partners, the positron and antineutrino, are examples of leptons. These types of particle do not appear to be composed of any smaller particles and are, therefore, considered to be fundamental particles.

The emission of electrons or positrons from nuclei was discussed earlier in this topic (β-decay page 172). During the decay of a neutron in the nucleus, a proton is formed and an electron and antineutrino emitted. In terms of the fundamental particles, quarks, the reaction can be shown as follows:

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}$$

u	u
d	u
d	d

The quark flavour is not conserved as a down quark has changed to an up quark. The reaction cannot be due to the strong force. The β-decay must be due to another force. This force is called the **weak force** or **weak interaction**.

The total lepton number before a reaction is equal to the total lepton number after the reaction.

The lepton number is +1 for the particle and –1 for the antiparticle.

The total lepton number before the reaction is zero in the β^--decay above. The lepton numbers for the particles after the reaction are +1 for the electron and –1 for the antineutrino, giving a total of zero.

Example

Describe the reaction where a proton in the nucleus turns into a neutron and emits a β-particle in terms of the quark model.

$${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + {}^{0}_{0}\nu$$

u	u
u	d
d	d

An up quark changes into a down quark.

Now it's your turn

6 What is the difference between a hadron and a lepton?

Summary

- An atom consists of a nucleus containing protons and neutrons surrounded by orbiting electrons.
- Most of the mass of an atom is contained in its nucleus.
- An atom is neutral as it contains an equal number of protons and electrons.
- Atoms which have gained or lost electrons are charged, and are called ions.
- The nucleon number A of a nucleus is the number of nucleons (protons and neutrons) in the nucleus.
- The proton number Z of a nucleus is the number of protons in the nucleus; hence the number of neutrons in the nucleus is $A - Z$.
- A nucleus (chemical symbol X) may be represented by: ${}^{\text{nucleon number}}_{\text{proton number}}\mathrm{X}$
- Isotopes are different forms of the same element, that is, nuclei with the same proton number but with different nucleon numbers.
- An α-particle is a helium nucleus (two protons and two neutrons).
- A β-particle is a fast-moving electron.
- γ-radiation consists of short-wavelength electromagnetic waves.
- In nuclear notation the emissions are represented as: α-particle ${}^{4}_{2}He$; β^--particle ${}^{0}_{-1}e$ or β^+-particle ${}^{0}_{+1}e$; γ-radiation ${}^{0}_{0}\gamma$.
- α-emission reduces the nucleon number of the parent nucleus by 4, and reduces the proton number by 2.
- β-emission causes no change to the nucleon number of the parent nucleus, and increases or decreases the proton number by 1.
- γ-emission causes no change to nucleon number or proton number of the parent nucleus.
- Radioactive decay is a spontaneous, random process.
- The Rutherford α-particle experiment confirmed the nuclear model of the atom: the atom consists of a small, positively-charged nucleus, surrounded by negatively-charged electrons in orbit about the nucleus and that the vast majority of the mass of the atom is in the nucleus.
- The diameter of the nucleus is about 10^{-15} m; the diameter of the atom is about 10^{-10} m.
- Electron diffraction gives evidence for the regular arrangement of atoms in crystals, and allows the measurement of the distance between planes of atoms in solids.

- For every type of subatomic particle there is an antimatter particle which has the same mass but opposite electrical charge.
- The antiparticle of the electron is called the positron.
- Protons and neutrons are hadrons and are affected by the strong force.
- During hadron reactions, charge and strangeness are conserved.
- The simple quark model has three flavours of quark (up, down and strange) together with their antiquarks.
- Protons are composed of quarks up, up and down, and neutrons of quarks up, down and down.
- Electrons and neutrinos are leptons which are fundamental particles and are affected by a weak interaction.
- During β⁻ decay: ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$ (electron) + ${}^{0}_{0}\bar{\upsilon}$ (antineutrino)
- During β⁺ decay: ${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{1}e$ (positron) + ${}^{0}_{0}\upsilon$ (neutrino)
- The energy of subatomic particles is often measured in eV or MeV.

Examination style questions

1 You are provided with a radioactive source which could be emitting α- or β-particles, or γ-radiation, or any combination of these. Describe a simple experiment, based on their relative penetrating qualities, you might carry out to determine the nature of the radiation(s) being emitted.

2 Explain the changes that take place to the nucleus of an atom when it emits:

a an α-particle,
b a β-particle,
c γ-radiation.

3 Complete the following radioactive series.

$${}^{235}_{92}U \rightarrow {}^{?}_{?}Y + {}_{?}He$$
$${}^{?}_{?}Y \rightarrow {}^{?}_{?}Z + {}^{0}_{-1}e$$
$${}^{?}_{?}Z \rightarrow {}^{?}_{?}Z + {}^{?}_{?}?$$

4 Calculate the speed of

a an electron with kinetic energy of 1.5 keV,
b an α-particle with kinetic energy of 1.5 keV.

5 A stationary radium nucleus (${}^{224}_{88}Ra$) of mass 224 u spontaneously emits an α-particle. The α-particle is emitted with an energy of 9.2×10^{-13} J, and the reaction gives rise to a nucleus of radon (Rn).

a Write down a nuclear equation to represent α-decay of the radium nucleus.
b Show that the speed with which the α-particle is ejected from the radium nucleus is 1.7×10^{7} m s^{-1}.
c Calculate the speed of the radon nucleus on emission of the α-particle. Explain how the principle of conservation of momentum is applied in your calculation.

6 When an α-particle travels through air, it loses energy by ionisation of air molecules. For every air molecule ionised, approximately 5.6×10^{-18} J of energy is lost by the α-particle.

a Suggest a typical value for the range of an α-particle in air. Hence estimate the number of air molecules ionised per millimetre of the path of the α-particle, given that the α-particle has initial energy 9.2×10^{-13} J.
b It has been discovered that the number of ionisations per unit length of the path of an α-particle suddenly increases just before the α-particle stops. State, with a reason, the effect that this observation will have on your estimate.

7 a The radioactive decay of some nuclei gives rise to the emission of α-particles.
State
i what is meant by an α-particle, *[1]*
ii two properties of α-particles. *[2]*

b One possible nuclear reaction involves the bombardment of a stationary nitrogen-14 nucleus by an α-particle to form oxygen-17 and another particle.
i Copy and complete the nuclear equation for this reaction. *[2]*

$${}^{14}_{7}N + {}^{\cdots\cdots}_{\cdots\cdots}\alpha \longrightarrow {}^{17}_{8}O + \cdots\cdots\cdots\cdots\cdots$$

ii The total mass–energy of the nitrogen-14 nucleus and the α-particle is less than that of the particles resulting from the reaction. This mass–energy difference is 1.1 MeV.
1 Suggest how it is possible for mass–energy to be conserved in this reaction. *[1]*
2 Calculate the speed of an α-particle having kinetic energy of 1.1 MeV. *[4]*

Cambridge International AS and A level Physics, 9702/22 May/June 2010 Q 7

8 a Evidence for the nuclear atom was provided by the α-particle scattering experiment. State the results of this experiment. *[2]*

b Give estimates for the diameter of
i an atom, *[1]*
ii a nucleus. *[1]*

Cambridge International AS and A level Physics, 9702/02 Oct/Nov 2007 Q 7

9 **a** Uranium (U) has at least fourteen isotopes. Explain what is meant by *isotopes*. *[2]*

b One possible nuclear reaction involving uranium is

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \longrightarrow ^{141}_{56}\text{Ba} + ^{92}_{Z}\text{Kr} + x\,^{1}_{0}\text{n} + \text{energy}.$$

i State three quantities that are conserved in a nuclear reaction. *[3]*

ii For this reaction, determine the value of

1 *Z*, *[1]*

2 *x*. *[1]*

Cambridge International AS and A level Physics, 9702/21 Oct/Nov 2010 Q 7

10 **a** β-radiation is emitted during the spontaneous radioactive decay of an unstable nucleus.

i State the nature of a β-particle. *[1]*

ii State two properties of β-radiation. *[2]*

iii Explain the meaning of *spontaneous radioactive decay*. *[1]*

b The following equation represents the decay of a nucleus of hydrogen-3 by the emission of a β-particle. Copy and complete the equation.

$$^{3}_{1}\text{H} \longrightarrow ^{\cdots\cdots}_{\cdots\cdots}\text{He} + ^{\cdots\cdots}_{\cdots\cdots}\beta$$ *[2]*

c The β-particle is emitted with an energy of 5.7×10^{3} eV. Calculate the speed of the β-particle. *[3]*

d A different isotope of hydrogen is hydrogen-2 (deuterium). Describe the similarities and differences between the atoms of hydrogen-2 and hydrogen-3. *[2]*

Cambridge International AS and A level Physics, 9702/23 Oct/Nov 2012 Q 6

11 Uranium-236 ($^{236}_{92}$U) and uranium-237 ($^{237}_{92}$U) are both radioactive. Uranium-236 is an α-emitter and uranium-237 is a β-emitter.

a Distinguish between an α-particle and a β-particle. *[4]*

b The grid of Fig. 26.13 shows some proton numbers *Z* on the x-axis and the number *N* of neutrons in the nucleus on the y-axis.

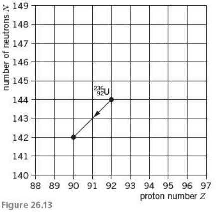

Figure 26.13

The α-decay of uranium-236 ($^{236}_{92}$U) is represented on the grid. This decay produces a nucleus of thorium (Th).

i Write down the nuclear equation for this α-decay. *[2]*

ii Copy Fig. 26.13, mark the position for a nucleus of

1 Uranium-237 (mark this position with the letter U),

2 Neptunium, the nucleus produced by the β-decay of uranium-237 (mark this position with the letters Np). *[2]*

Cambridge International AS and A level Physics, 9702/02 May/June 2008 Q 7

26. PARTICLE AND NUCLEAR PHYSICS MAY/JUNE ----2005-2015

Q1

8 Fig. 8.1 shows the position of Neptunium-231 ($^{231}_{93}Np$) on a diagram in which nucleon number (mass number) A is plotted against proton number (atomic number) Z.

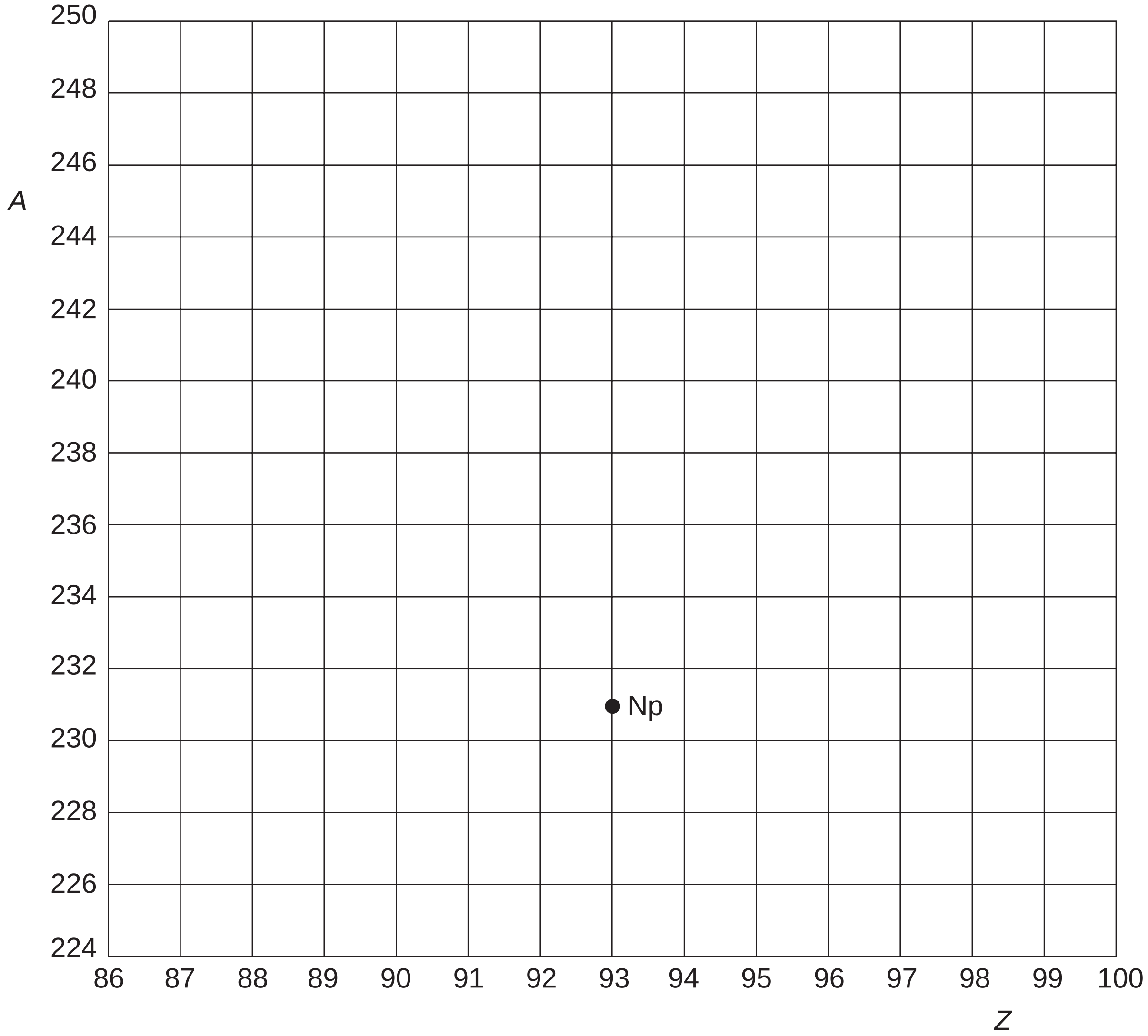

Fig. 8.1

(a) Neptunium-231 decays by the emission of an α-particle to form protactinium.
On Fig. 8.1, mark with the symbol Pa the position of the isotope of protactinium produced in this decay. [1]

(b) Plutonium-243 ($^{243}_{94}Pu$) decays by the emission of a β-particle (an electron).
On Fig. 8.1, show this decay by labelling the position of Plutonium-243 as Pu and the position of the daughter product as D. [2]

Q2

7 The radioactive decay of a strontium (Sr) nucleus is represented in Fig. 7.1.

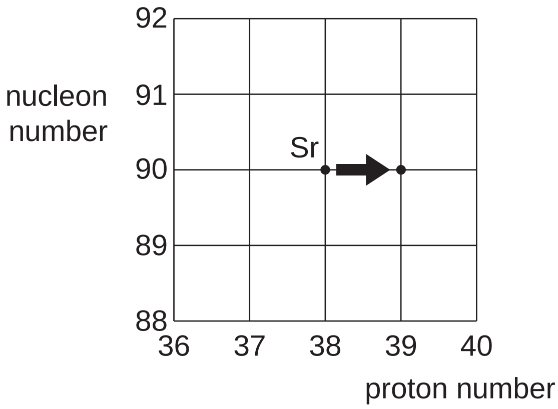

Fig. 7.1

(a) State whether Fig. 7.1 represents α-decay, β-decay or γ-decay.

....[1]

(b) One type of radioactive decay cannot be represented on Fig. 7.1.
Identify this decay and explain why it cannot be represented.

....

....

....[2]

Q3

7 Uranium-236 ($^{236}_{92}U$) and Uranium-237 ($^{237}_{92}U$) are both radioactive.
Uranium-236 is an α-emitter and Uranium-237 is a β-emitter.

(a) Distinguish between an α-particle and a β-particle.

....

....

....

....

....

.... [4]

(b) The grid of Fig. 7.1 shows some proton numbers *Z* on the *x*-axis and the number *N* of neutrons in the nucleus on the *y*-axis.

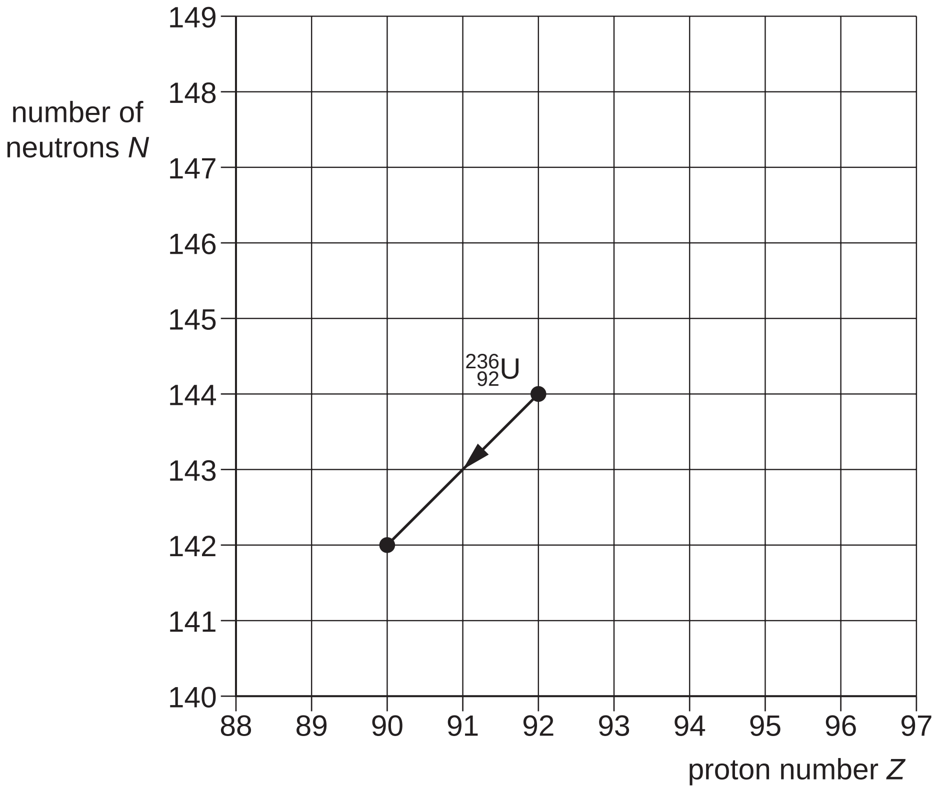

Fig. 7.1

The α-decay of Uranium-236 ($^{236}_{92}U$) is represented on the grid. This decay produces a nucleus of thorium (Th).

(i) Write down the nuclear equation for this α-decay.

....[2]

(ii) On Fig. 7.1, mark the position for a nucleus of

1. Uranium-237 (mark this position with the letter U),

2. Neptunium, the nucleus produced by the β-decay of Uranium-237 (mark this position with the letters Np). [2]

Q4

8 The spontaneous and random decay of a radioactive substance involves the emission of either α-radiation or β-radiation and/or γ-radiation.

(a) Explain what is meant by *spontaneous* decay.

....

....

.... [2]

(b) State the type of emission, one in each case, that

(i) is not affected by electric and magnetic fields,

.... [1]

(ii) produces the greatest density of ionisation in a medium,

.... [1]

(iii) does not directly result in a change in the proton number of the nucleus,

.... [1]

(iv) has a range of energies, rather than discrete values.

.... [1]

Q5

8 The spontaneous and random decay of a radioactive substance involves the emission of either α-radiation or β-radiation and/or γ-radiation.

(a) Explain what is meant by *spontaneous* decay.

....

....

.... [2]

(b) State the type of emission, one in each case, that

(i) is not affected by electric and magnetic fields,

.... [1]

(ii) produces the greatest density of ionisation in a medium,

.... [1]

(iii) does not directly result in a change in the proton number of the nucleus,

.... [1]

(iv) has a range of energies, rather than discrete values.

.... [1]

Q6

7 **(a)** The radioactive decay of some nuclei gives rise to the emission of α-particles. State

(i) what is meant by an α-particle,

.... [1]

(ii) two properties of α-particles.

1. ....

....

2. ....

....
[2]

(b) One possible nuclear reaction involves the bombardment of a stationary nitrogen-14 nucleus by an α-particle to form oxygen-17 and another particle.

(i) Complete the nuclear equation for this reaction.

$${}^{14}_{7}\mathrm{N} + {}^{\ldots\ldots}_{\ldots\ldots}\alpha \rightarrow {}^{17}_{8}\mathrm{O} + \ldots\ldots\ldots\ldots\ldots\ldots$$ [2]

(ii) The total mass-energy of the nitrogen-14 nucleus and the α-particle is less than that of the particles resulting from the reaction. This mass-energy difference is 1.1 MeV.

1. Suggest how it is possible for mass-energy to be conserved in this reaction.

....

.... [1]

2. Calculate the speed of an α-particle having kinetic energy of 1.1 MeV.

speed = ... m s^{-1} [4]

Q7

7 **(a)** The spontaneous decay of polonium is shown by the nuclear equation

$$^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + \text{X}.$$

(i) State the composition of the nucleus of X.

....

.... [1]

(ii) The nuclei X are emitted as radiation. State two properties of this radiation.

1. ....

....

2. ....

....

[2]

(b) The mass of the polonium (Po) nucleus is greater than the combined mass of the nuclei of lead (Pb) and X. Use a conservation law to explain qualitatively how this decay is possible.

....

....

.... [3]

Q8

7 **(a)** A nuclear reaction occurs when a uranium-235 nucleus absorbs a neutron. The reaction may be represented by the equation:

$$^{235}_{92}\text{U} + {}^{W}_{X}\text{n} \rightarrow {}^{93}_{37}\text{Rb} + {}^{141}_{Z}\text{Cs} + Y\,{}^{W}_{X}\text{n}$$

State the number represented by the letter

W ....

X ....

Y ....

Z ....

[3]

(b) The sum of the masses on the left-hand side of the equation in **(a)** is not the same as the sum of the masses on the right-hand side.

Explain why mass seems not to be conserved.

....

....

....[2]

Q9

7 A radioactive source emits α-radiation and γ-radiation.

Explain how it may be shown that the source does not emit β-radiation using

(a) the absorption properties of the radiation,

....

....

....

....

.... [2]

(b) the effects of a magnetic field on the radiation.

....

....

....

....

.... [2]

Q10

7 A polonium nucleus $^{210}_{84}Po$ is radioactive and decays with the emission of an α-particle. The nuclear reaction for this decay is given by

$$^{210}_{84}Po \longrightarrow {}^{W}_{X}Q + {}^{Y}_{Z}\alpha.$$

(a) **(i)** State the values of *W* ....

X ....

Y ....

Z ....

[2]

(ii) Explain why mass seems not to be conserved in the reaction.

....

....[2]

(b) The reaction is spontaneous. Explain the meaning of *spontaneous*.

....

....[1]

Q11

7 A uranium-235 nucleus absorbs a neutron and then splits into two nuclei. A possible nuclear reaction is given by

$$^{235}_{92}\mathrm{U} \; + \; ^{a}_{b}\mathrm{n} \; \longrightarrow \; ^{93}_{37}\mathrm{Rb} \; + \; ^{c}_{d}\mathrm{X} \; + \; 2\,^{a}_{b}\mathrm{n} \; + \; \text{energy.}$$

(a) State the constituent particles of the uranium-235 nucleus.

.... [1]

(b) Complete Fig. 7.1 for this reaction.

	value
a	
b	
c	
d	

[3]

Fig. 7.1

(c) Suggest a possible form of energy released in this reaction.

.... [1]

(d) Explain, using the law of mass-energy conservation, how energy is released in this reaction.

....

....

.... [2]

Q12

7 The equation represents the spontaneous radioactive decay of a nucleus of bismuth-212.

$$^{212}_{83}\text{Bi} \rightarrow \text{X} + {}^{208}_{81}\text{T}l + 6.2\,\text{MeV}$$

(a) **(i)** Explain the meaning of *spontaneous* radioactive decay.

....

....[1]

(ii) State the constituent particles of X.

....[1]

(b) **(i)** Use the conservation of mass-energy to explain the release of 6.2 MeV of energy in this reaction.

....

....

....[2]

(ii) Calculate the energy, in joules, released in this reaction.

energy = ... J [1]

26. PARTICLE AND NUCLEAR PHYSICS OCT/NOV ----2004-2014

Q1

7 The α-particle scattering experiment provided evidence for the existence of a nuclear atom.

(a) State what could be deduced from the fact that

(i) most α-particles were deviated through angles of less than 10°,

....

....

.... [2]

(ii) a very small proportion of the α-particles was deviated through angles greater than 90°.

....

....

.... [2]

Q2

7 **(a)** Evidence for the nuclear atom was provided by the α-particle scattering experiment. State the results of this experiment.

....

....

....

.... [2]

(b) Give estimates for the diameter of

(i) an atom,

....[1]

(ii) a nucleus.

....[1]

Q3

8 Thoron is a radioactive gas. The variation with time *t* of the detected count rate *C* from a sample of the gas is shown in Fig. 8.1.

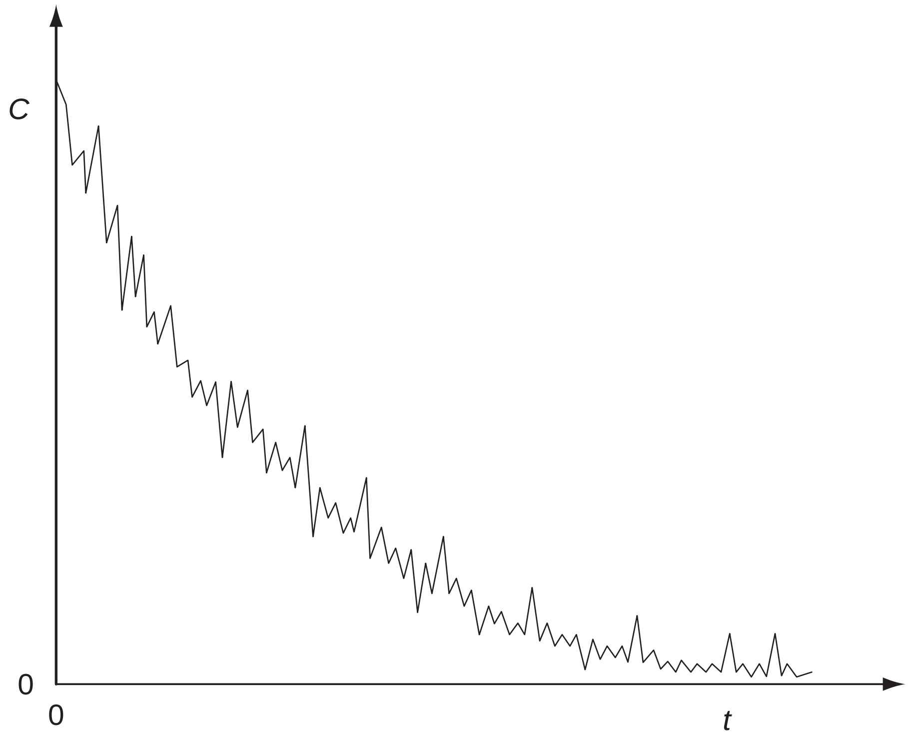

Fig. 8.1

Radioactive decay is said to be a random and spontaneous process.

(a) Explain, by reference to radioactive decay, what is meant by a *random* process.

....

....

.... [2]

(b) State the feature of Fig. 8.1 which indicates that the process is

(i) a decay process,

.... [1]

(ii) random.

.... [1]

(c) A second similar sample of thoron is prepared but it is at a much higher temperature. The variation with time of the count rate for this second sample is determined. State the feature of the decay curves for the two samples that suggests that radioactive decay is a spontaneous process.

....

.... [1]

Q4

7 Tungsten-184 ($^{184}_{74}W$) and tungsten-185 ($^{185}_{74}W$) are two isotopes of tungsten.

Tungsten-184 is stable but tungsten-185 undergoes β-decay to form rhenium (Re).

(a) Explain what is meant by *isotopes*.

....

....

....

.... [2]

(b) The β-decay of nuclei of tungsten-185 is spontaneous and random.

State what is meant by

(i) *spontaneous* decay,

....

.... [1]

(ii) *random* decay.

....

.... [1]

(c) Complete the nuclear equation for the β-decay of a tungsten-185 nucleus.

$^{185}_{74}W \rightarrow$ …………… + ……………… [2]

Q5

7 **(a)** Uranium (U) has at least fourteen isotopes.
Explain what is meant by *isotopes*.

....

....

.... [2]

(b) One possible nuclear reaction involving uranium is

$$ {}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{Z}\text{Kr} + x\,{}^{1}_{0}\text{n} + \text{energy.} $$

(i) State three quantities that are conserved in a nuclear reaction.

1. ....

....

2. ....

....

3. ....

....
[3]

(ii) For this reaction, determine the value of

1. *Z*,

Z = ... [1]

2. *x*.

x = ... [1]

Q6

7 The results of the α-particle scattering experiment provided evidence for the existence and small size of the nucleus.

(a) State the result that provided evidence for

(i) the small size of the nucleus, compared with the atom,

....

....

....[2]

(ii) the nucleus being charged and containing the majority of the mass of the atom.

....

....

....[2]

(b) The α-particles in this experiment originated from the decay of a radioactive nuclide. Suggest two reasons why β-particles from a radioactive source would be inappropriate for this type of scattering experiment.

1. ....

....

2. ....

....

[2]

Q7

9 **(a)** Explain what is meant by *radioactive decay*.

....

....

.... [2]

(b) **(i)** State how the random nature of radioactive decay may be inferred from observations of the count rate.

....

.... [1]

(ii) A radioactive source has a long half-life so that, over a period of several days, its rate of decay remains constant.
State the effect, if any, of a rise in temperature on this decay rate.

.... [1]

(iii) Suggest why some radioactive sources are found to contain traces of helium gas.

....

....

.... [2]

Q8

7 **(a)** Two isotopes of the element uranium are ${}^{235}_{92}\text{U}$ and ${}^{238}_{92}\text{U}$.

Explain the term *isotope*.

....

....

.... [2]

(b) **(i)** In a nuclear reaction, proton number and neutron number are conserved. Other than proton number and neutron number, state a quantity that is conserved in a nuclear reaction.

.... [1]

(ii) When a nucleus of uranium-235 absorbs a neutron, the following reaction may take place.

$$ {}^{235}_{92}\text{U} + {}^{a}_{b}\text{n} \longrightarrow {}^{141}_{x}\text{Ba} + {}^{y}_{36}\text{Kr} + 3\,{}^{a}_{b}\text{n} $$

State the values of *a*, *b*, *x* and *y*.

a = ...

b = ...

x = ...

y = ...
[3]

(c) When the nucleus of ${}^{238}_{92}\text{U}$ absorbs a neutron, the nucleus decays, emitting an α-particle. State the proton number and nucleon number of the nucleus that is formed as a result of the emission of the α-particle.

proton number = ...

nucleon number = ...
[2]

Q9

7 **(a)** State the experimental observations that show radioactive decay is

(i) spontaneous,

....

....[1]

(ii) random.

....

....[1]

(b) On Fig. 7.1, complete the charge and mass of α-particles, β-particles and γ-radiation. Give example speeds of α-particles and γ-radiation emitted by a laboratory source.

	α-particle	β-particle	γ-radiation
charge			0
mass	4u		
speed		up to 0.99c	

Fig. 7.1

[3]

(c) Explain the process by which α-particles lose energy when they pass through air.

....

....

....[2]

Q10

7 A nuclear reaction between two helium nuclei produces a second isotope of helium, two protons and 13.8 MeV of energy. The reaction is represented by the following equation.

$$^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{\dots\dots}_{\dots\dots}\text{He} + 2\,{}^{\dots\dots}_{\dots\dots}\text{p} + 13.8\,\text{MeV}$$

(a) Complete the nuclear equation. [2]

(b) By reference to this reaction, explain the meaning of the term *isotope*.

....

....

....[2]

(c) State the quantities that are conserved in this nuclear reaction.

....

....

....

....

....[2]

(d) Radiation is produced in this nuclear reaction.

State

(i) a possible type of radiation that may be produced,

....[1]

(ii) why the energy of this radiation is less than the 13.8 MeV given in the equation.

....[1]

(e) Calculate the minimum number of these reactions needed per second to produce power of 60 W.

number = ... s^{-1} [2]

Q11

6 **(a)** β-radiation is emitted during the spontaneous radioactive decay of an unstable nucleus.

(i) State the nature of a β-particle.

.... [1]

(ii) State two properties of β-radiation.

1. ....

2. ....
[2]

(iii) Explain the meaning of *spontaneous radioactive decay*.

....

.... [1]

(b) The following equation represents the decay of a nucleus of hydrogen-3 by the emission of a β-particle.

Complete the equation.

$${}^{3}_{1}\text{H} \rightarrow {}^{\cdots\cdots}_{\cdots\cdots}\text{He} + {}^{\cdots\cdots}_{\cdots\cdots}\beta$$ [2]

(c) The β-particle is emitted with an energy of 5.7×10^{3} eV.

Calculate the speed of the β-particle.

speed = ... m s^{-1} [3]

(d) A different isotope of hydrogen is hydrogen-2 (deuterium). Describe the similarities and differences between the atoms of hydrogen-2 and hydrogen-3.

....

....

.... [2]

(b) A source of α-particles is uranium-238. The nuclear reaction for the emission of α-particles is represented by

$$^{238}_{92}\text{U} \rightarrow {}^{W}_{X}\text{Q} + {}^{Y}_{Z}\alpha.$$

State the values of *W*...............

X ....

Y ....

Z ....

[2]

(c) A source of β-particles is phosphorus-32. The nuclear reaction for the emission of β-particles is represented by

$$^{32}_{15}\text{P} \rightarrow {}^{A}_{B}\text{R} + {}^{C}_{D}\beta.$$

State the values of *A* ....

B ....

C ....

D ....

[1]

Q12

7 In the decay of a nucleus of ${}^{210}_{84}Po$, an α-particle is emitted with energy 5.3 MeV.

The emission is represented by the nuclear equation

$$ {}^{210}_{84}Po \longrightarrow {}^{A}_{B}X + \alpha + \text{energy} $$

(a) **(i)** On Fig. 7.1, complete the number and name of the particle, or particles, represented by A and B in the nuclear equation.

	number	name of particle or particles
A		
B		

Fig. 7.1

[1]

(ii) State the form of energy given to the α-particle in the decay of ${}^{210}_{84}Po$.

....[1]

(b) A sample of polonium ${}^{210}_{84}Po$ emits 7.1×10^{18} α-particles in one day.

Calculate the mean power output from the energy of the α-particles.

power = ... W [2]

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