Structure of atom and nucleus

Read the first two tutorials on *Particle Physics and Quantum Phenomena*, in the AS PHYA1 section on the Antonine Education Website (http://www.antonine-education.co.uk) and do the 'test yourself' questions. The links are below.

http://bit.ly/29JnNgW

http://bit.ly/2aao6GQ

Read the notes on the next two pages.

Then complete the questions in this booklet. The answers are at the end so that you can check that you've got them right.

In your first lesson you will do a short, 30 minute test on this material. The questions will be taken from this work book, with some of the numbers changed, so if you do this work properly it should be easy.

The opposite is also true!

The Physics Team.

Structure of atom and nucleus

1 Matter and radiation

1.1 Inside the atom

Learning objectives:

- What is inside an atom?
- What are isotopes?
- How do we represent different atoms?

Specification reference: 3.1.1

Study tip

Don't mix up 'n' words – nucleus, neutron, nucleon, nuclide!

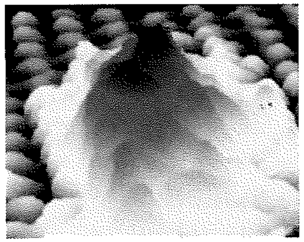


Figure 1 *Atoms seen using a scanning tunnelling microscope (STM)*

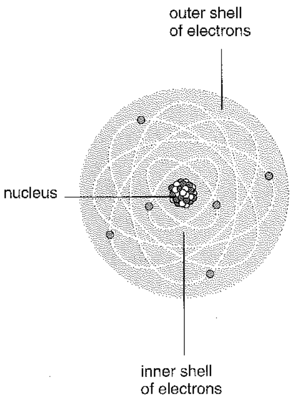


Figure 2 *Inside the atom*

The structure of the atom

Atoms are so small (less than a millionth of a millimetre in diameter) that we need to use an electron microscope to see images of them. Although we cannot see inside them, we know, from Rutherford's alpha-scattering investigations, that every atom contains

- a positively charged nucleus composed of protons and neutrons
- electrons that surround the nucleus.

We use the word **nucleon** for a proton or a neutron in the nucleus.

Each electron has a negative charge. Because the nucleus is positively charged, the electrons are held in the atom by the electrostatic force of attraction between them and the nucleus. Rutherford's investigations showed that the nucleus contains most of the mass of the atom and its diameter is of the order of 0.00001 times the diameter of a typical atom.

Table 1 shows the charge and the mass of the proton, the neutron and the electron in SI units (coulombs for charge and kilograms for mass) and relative to the charge and mass of the proton. Notice that:

1 The electron has a much smaller mass than the proton or the neutron.
2 The proton and the neutron have almost equal mass.
3 The electron has equal and opposite charge to the proton. The neutron is uncharged.

Table 1 *Inside the atom*

	charge		mass	
	/ C	/ charge of the proton	/ kg	/ mass of proton
proton	$+1.60 \times 10^{-19}$	1	1.67×10^{-27}	1
neutron	0	0	1.67×10^{-27}	1
electron	-1.60×10^{-19}	−1	9.11×10^{-31}	0.0005

Isotopes

Every atom of a given element has the same number of protons as any other atom of the same element. The proton number is usually called the **atomic number** (symbol Z) of the element. For example:

- $Z = 6$ for carbon because every carbon atom has six protons in its nucleus.
- $Z = 92$ for uranium because every uranium atom has 92 protons in its nucleus.

The atoms of an element can have different numbers of neutrons. Atoms of the same element with different numbers of neutrons are called **isotopes**.

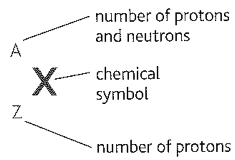
For example, the most abundant isotope of natural uranium contains 146 neutrons and the next most abundant contains 143 neutrons.

Isotopes are atoms with the same number of protons and different numbers of neutrons.

The total number of protons and neutrons in an atom is called the **nucleon number** (symbol A) or sometimes the **mass number** of the atom. This is because it is almost numerically equal to the mass of the atom in relative units (where the mass of a proton or neutron is approximately 1). A **nucleon** is a neutron or a proton in the nucleus.

We label the isotopes of an element according to their atomic number Z, their mass number A and the chemical symbol of the element. Figure 3 shows how we do this. Notice that:

- Z is at the bottom left of the element symbol and gives the number of protons in the nucleus.
- A is at the top left of the element symbol and gives the number of protons and neutrons in the nucleus.
- The number of neutrons in the nucleus $= A - Z$.



Example: the symbol for the uranium isotope with 92 protons and 146 neutrons is $^{238}_{92}\text{U}$ (or sometimes U-238)

Figure 3 *Isotope notation*

Each type of nucleus is called a **nuclide** and is labelled using the isotope notation. For example, a nuclide of the carbon isotope $^{12}_{6}\text{C}$ has two fewer neutrons and two fewer protons than a nuclide of the oxygen isotope $^{16}_{8}\text{O}$.

Specific charge

The **specific charge** of a charged particle is defined as its charge divided by its mass. We can calculate the specific charge of a charged particle if we know the charge and the mass of the particle. For example:

A nucleus of $^{1}_{1}\text{H}$ has a charge of 1.60×10^{-19} C and a mass of 1.67×10^{-27} kg. Its specific charge is therefore $9.58 \times 10^{7}\,\text{C kg}^{-1}$.

The electron has a charge of -1.60×10^{-19} C and a mass of 9.11×10^{-31} kg. Its specific charge is therefore $1.76 \times 10^{11}\,\text{C kg}^{-1}$. Note that the electron has the largest specific charge of any particle.

An ion of the magnesium isotope $^{24}_{12}\text{Mg}$ has a charge of $+3.2 \times 10^{-19}$ C and a mass of 3.98×10^{-26} kg. Its specific charge is therefore $8.04 \times 10^{6}\,\text{C kg}^{-1}$.

1.2 Stable and unstable nuclei

Learning objectives:

- What keeps the protons and neutrons in a nucleus together?
- Why are some nuclei stable and others unstable?
- What happens when an unstable nucleus emits an alpha particle or a beta minus particle?

Specification reference: 3.1.1

How Science Works

Measuring background radiation

Use a Geiger tube and a counter to detect and measure background radioactivity.

The strong nuclear force

A stable isotope has nuclei that do not disintegrate, so there must be a force holding them together. We call this force the **strong nuclear force** because it overcomes the electrostatic force of repulsion between the protons in the nucleus and (except in unstable nuclei) keeps the protons and neutrons together.

Some further important points about the strong nuclear force are:

- Its range is no more than about 3–4 femtometres (fm), where 1 fm $= 10^{-15}$ m $= 0.000\,000\,000\,000\,001$ m. This range is about the same as the diameter of a small nucleus. In comparison, the electrostatic force between two charged particles has an infinite range (although it decreases as the range increases).
- It has the same effect between two protons as it does between two neutrons or a proton and a neutron.
- It is an attractive force from 3–4 fm down to about 0.5 fm. At separations smaller than this, it is a repulsive force that acts to prevent neutrons and protons being pushed into each other.

Figure 1 shows how the strong nuclear force varies with separation between two protons or neutrons. Notice that the equilibrium separation is where the force curve crosses the x-axis.

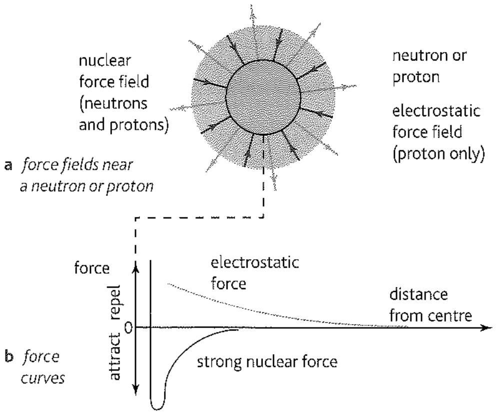


Figure 1 *The strong nuclear force*

Radioactive decay

Naturally-occurring radioactive isotopes release three types of radiation.

1 **Alpha radiation** consists of alpha particles which each comprise two protons and two neutrons. The symbol for an alpha particle is ${}^{4}_{2}\alpha$ because its proton number is 2 and its mass number is 4.

Figure 2 shows what happens to an unstable nucleus of an element X when it emits an alpha particle. Its nucleon number A decreases by 4

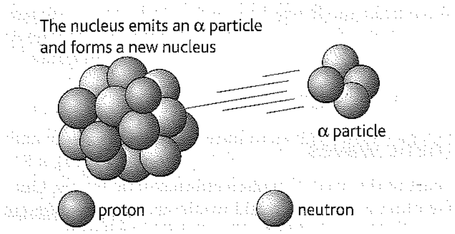


Figure 2 *Alpha particle emission (not to scale)*

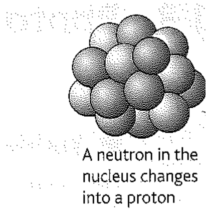


Figure 3 *Beta particle em*

and its atomic number Z decreases by 2. As a result of the change, the product nucleus belongs to a different element Y. 1

We can represent this change by means of the equation below:

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

2 **Beta radiation** consists of fast-moving electrons. The symbol for an electron as a beta particle is ${}^{0}_{-1}\beta$ (or β^-) because its charge is equal and opposite to that of the proton and its mass is much smaller than the proton's mass.

Figure 3 shows what happens to an unstable nucleus of an element X when it emits a β^- particle. This happens as a result of a neutron in the nucleus changing into a proton. The beta particle is created when the change 2 happens and is emitted instantly. In addition, an antiparticle with no charge, called an **antineutrino** (symbol $\bar{\nu}$), is emitted. You will learn more about antiparticles in Topic 1.4. Because a neutron changes into a proton in the nucleus, the atomic number increases by 1 but the nucleon number stays the same. As a result of the change, the product nucleus belongs to 3 a different element Y. This type of change happens to nuclei that have too many neutrons.

We can represent this change by means of the equation below:

$${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}\beta + \bar{\nu}$$

3 **Gamma radiation** (symbol γ) is electromagnetic radiation emitted by an unstable nucleus. It can pass through thick metal plates. It has no mass and no charge. It is emitted by a nucleus with too much energy, following an alpha or beta emission.

How Science Works

A very elusive particle!

When the energy spectrum of beta particles was first measured, it was found that beta particles were released with kinetic energies up to a maximum that depended on the isotope. The scientists at the time were puzzled why the energy of the beta particles varied up to a maximum, when each unstable nucleus lost a certain amount of energy in the process. Either energy was not conserved in the change 4 or some of it was carried away by mystery particles, which they called **neutrinos** and **antineutrinos**. This hypothesis was unproven for over 20 years until antineutrinos were detected. Antineutrinos were detected as a result of their interaction with cadmium nuclei in a large tank of water. This was installed next to a nuclear reactor as a controllable source of these very elusive particles. Now we know that billions of these elusive particles from the Sun sweep through our bodies every second without interacting!

Study tip

Remember what the numbers stand for in the decay equations on the next page.

Structure of atom and nucleus

Q1. (a) An ion of plutonium $^{239}_{94}Pu$ has an overall charge of $+1.6 \times 10^{-19}$ C.

For this ion state the number of

(i) protons ....

(ii) neutrons ....

(iii) electrons ....

(3)

(b) Plutonium has several *isotopes*.

Explain the meaning of the word isotopes.

....

....

....

(2)
(Total 5 marks)

Q2. (a) How many protons, neutrons and electrons are there in an atom of $^{14}_{6}C$?

.... protons

.... neutrons

.... electrons

(2)

(b) The $^{14}_{6}C$ atom loses two electrons.
For the ion formed;

(i) calculate its charge in C,

....

(ii) state the number of nucleons it contains,

....

(iii) calculate the ratio $\frac{\text{charge}}{\text{mass}}$ in C kg^{-1}.

....

....

....

....

(4)
(Total 6 marks)

Q3. (a) How many protons, neutrons and electrons are there in an atom of caesium, $^{133}_{55}Cs$, which is the most abundant and stable *isotope* of caesium.

.... protons

.... neutrons

.... electrons

(2)

(b) (i) Explain what is meant by isotopes.

....

....

(ii) Write down an isotope $^{133}_{55}Cs$ that is likely to be a beta minus emitter.

....

(3)

Structure of atom and nucleus

Q4. (a) What are isotopes?

....

....

....

....

....

(2)

(b) One of the isotopes of nitrogen may be represented by $^{15}_{7}N$.

(i) State the number of each type of particle in its nucleus.

....

....

(ii) Determine the ratio $\frac{\text{charge}}{\text{mass}}$, in C kg^{-1}, of its nucleus.

....

....

....

....

(4)

(c) (i) What is the charge, in C, of an atom of $^{15}_{7}N$ from which a single electron has been removed?

....

(ii) What name is used to describe an atom from which an electron has been removed?

....

(2)
(Total 8 marks)

Q5. (a) Name the constituent of an atom which

(i) has zero charge,

....

(ii) has the largest charge to mass ratio,

....

(iii) when removed leaves a different isotope of the element.

....

(3)

(b) An α particle is the same as a nucleus of helium, ${}^{4}_{2}He$.

The equation

$${}^{229}_{90}Th \longrightarrow {}^{X}_{Y}Ra + \alpha$$

represents the decay of thorium by the emission of an α particle.

Determine

(i) the values of X and Y, shown in the equation,

X = ...

Y = ...

(ii) the ratio $\dfrac{\text{mass of } {}^{X}_{Y}\text{Ra nucleus}}{\text{mass of } \alpha \text{ particle}}$

....

....

....

(3)
(Total 6 marks)

Structure of atom and nucleus

Q6. (a) (i) Determine the charge, in C, of a $^{239}_{92}U$ nucleus.

....

....

(ii) A positive ion with a $^{239}_{92}U$ nucleus has a charge of 4.80×10^{-19} C. Determine how many electrons are in this ion.

....

....

....

(4)

(b) A $^{239}_{92}U$ nucleus may decay by emitting **two** β^- particles to form a plutonium nucleus $^{X}_{Y}Pu$. State what X and Y represent and give the numerical value of each.

X ....

....

Y ....

....

(4)
(Total 8 marks)

Structure of atom and nucleus

Q7. (a) A stable atom contains 28 nucleons.

Write down a possible number of protons, neutrons and electrons contained in the atom.

.... protons

.... neutrons

.... electrons

(2)

(b) An unstable *isotope* of uranium may split into a caesium nucleus, a rubidium nucleus and four neutrons in the following process.

$$^{236}_{92}U \Rightarrow \ ^{137}_{55}Cs + \ ^{X}_{37}Rb + 4\,^{1}_{0}n$$

(i) Explain what is meant by isotopes.

....

....

....

(ii) How many neutrons are there in the $^{137}_{55}Cs$ nucleus?

....

(iii) Calculate the ratio $\frac{\text{charge}}{\text{mass}}$, in C kg^{-1}, for the $^{236}_{92}U$ nucleus.

....

....

....

(iv) Determine the value of X for the rubidium nucleus.

....

X = ...

(6)
(Total 8 marks)

Structure of atom and nucleus

Q8. A neutral atom of a radium isotope may be represented by $^{228}_{88}Ra$.

(a) (i) Name the constituents of this atom and state how many of each are present.

....

....

....

(3)

(ii) Which constituent of an atom has the largest specific charge?

....

(1)

(iii) This isotope of radium decays by β^- decay to form an element with symbol, Ac. Write down an equation that represents this decay.

(4)

(b) $^{A}_{Z}Ra$ is a neutral atom of a different isotope of radium. State a possible value for A and for Z.

A: ....

Z: ....

(2)
(Total 10 marks)

Structure of atom and nucleus

M1. (a) (i) 94 (protons) **(1)**

(ii) 145 (neutrons) **(1)**

(iii) 93 (electrons) **(1)**

3

(b) same number of protons[or same atomic number] **(1)**

different number of neutrons/nucleons[or different mass number] **(1)**

2

[5]

M2. (a) 6 (protons) and 6 (electrons) **(1)**
8 (neutrons) **(1)**

2

(b) (i) $(2 \times 1.6 \times 10^{-19}) = 3.2 \times 10^{-19}$ (C) **(1)**

(ii) 14 **(1)**

(iii) $m = 14 \times 1.67 \times 10^{-27}$ (kg) **(1)**

$\frac{Q}{M} = \left(\frac{3.2 \times 10^{-19}}{14 \times 1.67 \times 10^{-27}}\right) = 1.4 \times 10^{7}$ (C kg^{-1}) **(1)**

(1.37×10^{7} (C kg^{-1}))

(allow C.E for values from (i) and (ii))

4

[6]

M3. (a) 55 protons

55 electrons **(1)**

78 neutrons **(1)**

2

(b) (i) same number of protons **(1)**

different number of neutrons **(1)**

(ii) $^{134\rightarrow154}_{55}\mathrm{Cs}$ **(1)**

3

(c) specific charge (= charge/mass) = $55 \times 1.6 \times 10^{-19}/137 \times 1.67 \times 10^{-27}$ **(1)**

3.96×10^{7} **(1)** C kg^{-1} **(1)**

3

[8]

M4. (a) (atoms with) same number of protons/same atomic number **(1)**
different number of neutrons/mass number/ nucleons **(1)**

2

(b) (i) 7 protons **(1)**
8 neutrons **(1)**

(ii) $\left(\frac{\text{charge}}{\text{mass}}\right) = \frac{7 \times 1.6 \times 10^{-19}}{15 \times 1.67 \times 10^{-27}}$ **(1)**

= 4.5×10^{7} (C kg^{-1}) **(1)** (4.47×10^{7} (C kg^{-1}))
(allow C.E. for incorrect values in (b) (i))

4

(c) (i) (+) 1.6×10^{-19} (C) **(1)**

(ii) positive ion **(1)**

2

[8]

M5. (a) (i) neutron **(1)**

(ii) electron **(1)**

(iii) neutron **(1)**

3

(b) (i) (X =) 225 **(1)**(Y =) 88 **(1)**

(ii) $\left(\frac{\text{mass of } ^{225}_{88}\text{Ra}}{\text{mass of } \alpha \text{ particle}} = \frac{225}{4}\right)$ = 56(.3) **(1)**

(allow C.E. for value of X from (i))

3

[6]

M6. (a) (i) (charge) = $92 \times 1.60 \times 10^{-19}$
= 1.47×10^{-17} (C) **(1)**

(ii) (magnitude of ion charge) = 3(*e*) **(1)**
number of electrons (= 92 – 3) = 89 **(1)**

4

(b) X: number of nucleons [or number of neutrons plus protons or mass number] **(1)**
239 **(1)**
Y: number of protons [or atomic number] **(1)**
94 **(1)**

4

[8]

M7. (a) number of protons = number of electrons (e.g.14) **(1)**

number of protons + number of neutrons = 28 **(1)**

2

(b) (i) nuclei with the same number of protons **(1)**but different number of neutrons/nucleons **(1)**

(ii) (137 – 55) = 82 **(1)**

(iii) $\frac{Q}{m} = \frac{92 \times 1.60 \times 10^{-19}}{236 \times 1.67 \times 10^{-27}}$ **(1)**

= 3.73×10^{7} (C kg^{-1}) **(1)**

(iv) X (= 236 – 137 – 4) = 95 **(1)**

6

[8]

M8. (a) (i) 88 protons **(1)**

140 neutrons **(1)**

88 electrons **(1)**

3

(ii) electron **(1)**

1

(iii) $^{228}_{88}Ra \rightarrow ^{228}_{89}Ac + ^{0}_{-1}e + \overline{\nu_e}$ **(1)(1)(1)(1)**

4

(b) 228 ± 10 **(1)**

88 **(1)**

2

[10]