# The Structure of the Nucleus

## Composition of nuclei

The nucleus of an atom is made up of protons and neutrons. They have approximately the same mass. The proton is positively charged, whilst the neutron is not charged.

**Nucleon** – either a proton or a neutron.

We can represent a nucleus, X, in the form:

**Mass number**, A – number of nucleons in the nucleus of an atom.

**Atomic number**, Z – number of protons in the nucleus of an atom.

Z is also the number of electrons in a neutral atom.

1. Write down the nuclear notation ( ) for:
	1. A proton
	2. A hydrogen nucleus
	3. A neutron
2. Specify the nucleus of polonium, in the form given it has 84 protons and 125 neutrons:
3. Specify the nucleus of carbon, in the form given it has 6 protons and 6 neutrons:
4. Specify how many protons, neutrons and nucleons are in the following nuclei:
	1. – 2 protons, 2 neutrons, 4 nucleons
	2. – 1 proton, 0 neutrons, 1 nucleon
	3. – 91 protons, 140 neutrons, 231 nucleon

## The force between nucleons

Protons repel due to the electrostatic force, so another force must be present to hold the nucleus together at such small distances.

Indeed, the nuclear force is an attractive force that acts between nucleons. Also called the strong nuclear force, this force acts over a short range.

Neutrons in the nucleus act to shield the protons from each other and strengthen the attractive force.

Graph of nucleon force vs distance



1. Describe how the strong nuclear force changes with respect to distance in the diagram above.

## Isotopes

The number of protons determines the element. However, nuclei of a given element may have different numbers of neutrons.

**Isotopes** – nuclei with the same number of protons but different number of neutrons.

Isotopes have different mass numbers.

For example, carbon has 15 known isotopes, three of which are naturally occurring:

Isotopes are sometimes written, for example, as carbon-12, carbon-13, denoting the atomic number, that is, the number of protons and neutrons.

Although isotopes have different masses, they are chemically identical because the outer electronic structure (that is, the number of electrons) of an element determines its chemistry.

Some isotopes occur more frequently in nature.

## Mass defect and binding energy

Example: The mass of a helium nucleus (also called an alpha particle) is  kg.

If we add up the mass of 2 protons and 2 neutrons:

The mass of the alpha particle is less than the sum of all the masses of the constituent particles!

We can interpret this in terms of energy using Einstein’s famous equation relating energy and mass:

Where m is the mass and c is the speed of light in vacuum: . The missing mass, or mass defect, is converted to energy and released in forming the nucleus. Often the energy is released in the form of an emitted photon.

If the nucleus is stable, then it must have a lower energy than the separate particles, otherwise the separate particles would be preferred. In nature, minimum energy states are preferred. For example, consider a ball at the top of a hill; the ball will roll down until it reaches a position of stable equilibria, like a valley.

If we wanted to reverse the process and free the nucleons, we would have to put that energy back in, which is why we call this energy the binding energy:

The binding energy is analogous to the ionisation energy required to remove an electron from an atom.

**Mass defect** –difference between mass of nucleus and constituent particles.
**Binding energy** – energy required to remove particles from nucleus.

The binding energy of the alpha particle is then,

Compared to the ionisation energy needed to release an electron from hydrogen (13.6 eV), the energy required in nuclear processes are some 6 orders of magnitude higher! This is because the nuclear force is much stronger than the electrostatic force. Having said that, the helium nucleus is an *especially* stable nucleus with a high binding energy.

1. For lithium, with a mass of
	1. Calculate the mass defect:
	2. Calculate the binding energy in J and MeV:
2. When a nucleus of iron forms, a photon of energy 504 MeV is emitted. Calculate:
	1. The frequency of the photon
	2. The binding energy of
	3. The mass defect

## Conservation Laws in Nuclear Reactions

Unlike in chemical reactions, in nuclear reactions the products of the reaction can be different elements to the reactants. For example,

Similar to chemical equations, nuclear equations have rules:

### Conservation of charge

In nuclear reactions, charge is conserved. Hence the atomic number remains the same before and after the reaction.

For charge conservation, we represent electrons in nuclear equations as: .

### Conservation of nucleon number

The total number of nucleons remain constant in a reaction, although the type of nucleon may change. In chemical reactions the number of protons and neutrons are constant.

### Conservation of mass – energy

In a nuclear reaction, (and chemical reactions too), the total energy remains the same. Unlike in chemical reactions, the total mass of the product will be different to the total mass of the reactant.

 We can determine whether energy is absorbed or released by calculating the change in mass.

Increase in mass implies energy is absorbed.

Decrease in mass implies energy is released.

### Conservation of momentum

In a nuclear reactions, momentum is conserved:

We can use this law to predict the directions and velocities of the reaction products.

To illustrate how we can use this law, consider the decay of a Uranium-238 atom at rest:

Since the uranium was at rest,

Hence the particles must move in the opposite directions, because there are only two of them and momentum is conserved:

Hence,

Since, the helium weighs much less, it must have a much higher speed than the thorium:

That is, the helium has a speed roughly 58.5 times greater than the thorium nucleus. Similarly, we can calculate the ratio of the kinetic energies:

Therefore the helium has the greater kinetic energy, and this is generally true for smaller particles in other nuclear processes.

1. The Manhattan Project, the development of the atomic bomb, led to the discovery of the transuranic elements (elements beyond uranium in the periodic table). Plutonium, element 94, is formed by the bombardment of uranium-238 with neutrons. Complete the nuclear equations:
2. The isotope 235U decays into another element, emitting an alpha particle. Write a nuclear equation for the decay.
3. Plutonium-244 decays to form uranium-240, as shown in the reaction below:
4. If the plutonium is initially at rest, what can we say about the direction of the products?
5. Show that the velocity of the helium nucleus is approximately 60 times the speed of the uranium nucleus.
6. Given the following masses, calculate the binding energy of plutonium-244 and hence state whether energy is released or absorbed in the reaction:

plutonium-244, kg

uranium-240, 3kg

alpha particle , kg

 Give the energy in J and MeV.

## Application: the production of medical radioisotopes

**Radioisotopes** - the isotopes of an element that are radioactive.

Such nuclei are unstable and will emit particles and electromagnetic radiation such as gamma photons.

First we will look at producing radioisotopes and in the next section we will look at how they decay and also how they are used as a medical imaging tool.

Two main uses of medical radioisotopes:

* Diagnostic tool in imaging, for example in PET scans
* Therapeutic techniques, where radiation is used to damage certain cells

There are a few techniques for producing radioisotopes, involving collisions where a nuclei gains protons or neutrons or both. Addition of neutrons produces isotopes of the same element, while addition of protons will change the type of element.

### Adding neutrons to nuclei

Neutrons fired at low kinetic energy may be captured by the nuclei. Although neutrons have no charge and do not experience a repulsion force, the absorption is still not a simple process. Neutrons moving too fast may be deflected, pass through or shatter the nucleus.

Example: production of a radioactive isotope of phosphorus, phosphorus-32:

### Adding protons to nuclei

Since protons are charged, the protons require high kinetic energy to approach the nucleus and not be repelled.

In the sun the high temperatures provide the protons with enough speed to overcome the repulsion.

In the synthetic production of radioisotopes, we can accelerate protons by using a particle accelerator such as a cyclotron.

Example: production of a medical radioisotope, fluorine-18, commonly used in PET scans:

### Collision with other nuclei

We can also fire smaller, charged nuclei to produce radioisotopes. Again, the nuclei can be accelerated to high velocities using a cyclotron. For example, the medical radioisotope oxygen-15 is produced by colliding the hydrogen-2 isotope with nitrogen:

### Energy requirements

As radioisotopes are not stable, the mass defect of the reaction is often negative, indicating that energy must be absorbed.

This energy can be supplied by the kinetic energy of the collision particle. However the kinetic energy of the collision particle must be greater than the binding energy in order for conservation of momentum to hold. If the kinetic energy is equal to the binding energy, then the products would have no momentum.

1. What are some uses of phosphorus-32 (you can use the internet)?
* Tracer
* Cancer treatment
* Treatment of excess red blood cells (polycythemia)
1. Explain, using a nuclear equation, how phosphorus-32 may be produced using neutrons emitted from a nuclear fission reactor.
2. Explain using a nuclear equation, how the medical radioisotopes fluorine-18 and oxygen-15 may be produced using a cyclotron.