If matter can neither be created nor destroyed, how can a nuclear chain reaction produce a vast amount of energy in a short space of time?

Nuclear fission involves splitting the nucleus of an atom into lighter parts, for example by bombarding an atom with neutrons from a particle accelerator. However, when the mass of an atom of a neutral element is measured to six or more decimal places it is less than the calculated sum of the mass of neutrons, protons and electrons that make up the atom. This difference is called the **mass defect**.

Part 1: Calculating mass defect

In this example, the mass defect of uranium-235 (^{235}U) will be calculated. To start, we need exact measurements of the mass of a neutral ^{235}U, proton, neutron and electron.

These are listed below in **unified atomic mass units** (u). Using this scale a neutral carbon-12 atom is assigned the exact value of 12.000 000 u.

	mass (u)
mass of a neutral ^{235}U atom (this includes its electrons)	235.043 924
mass of a proton	1.007 276
mass of a neutron	1.008 665
mass of an electron	0.000 549

A neutral ^{235}U atom contains 92 protons, 92 electrons and 143 neutrons. The mass of the component particles and mass defect are calculated as follows:

	mass (u)	subtotal (u)
protons	92 x 1.007 276	92.669 392
neutrons	143 x 1.008 665	144.239 095
electrons	92 x 0.000 549	0.050 508
	total mass **(A)**	236.958 995
	mass of neutral ^{235}U atom **(B)**	235.043 924
	mass defect **(A - B)**	1.915 071

The mass defect is calculated in unified atomic mass units (u), which can be converted to kilograms using the conversion factor: 1 u = 1.6605×10^{-27} kg.

mass defect	= $1.915\ 071 \times (1.6605 \times 10^{-27})$ kg
	= $3.179\ 975 \times 10^{-27}$ kg

Part 2: Calculating binding energy

Mass defect can be used to calculate **binding energy**. This is the energy needed to break an atom into its constituent particles. It is calculated using Einstein's equation $E = mc^2$, where E is the binding energy in joules, m is the mass defect in kilograms, and c is the velocity of light in metres per second (3.00×10^8 m s^{-1}).

Again using ^{235}U as an example:

mass defect	$= 3.179\,975 \times 10^{-27}$ kg
binding energy, E	$= m\,c^2$
	$= 3.179\,975 \times 10^{-27} \times (3.00 \times 10^8)^2$
	$= 2.86 \times 10^{-10}$ J

This is the binding energy per neutral ^{235}U atom. Binding energy is usually quoted per nucleon as this gives a better idea about the stability of nuclei and a guide as to which elements are most likely to undergo fission. There are 235 nucleons in ^{235}U (92 protons and 143 neutrons) so the binding energy per nucleon is given by:

binding energy per nucleon	$= 2.86 \times 10^{-10} / 235$ J
	$= 1.22 \times 10^{-12}$ J

An alternative way of expressing energy is in electron volts (eV). The electron volt is defined as the energy acquired by an electron as it moves through a potential of one volt. The conversion factor for joules to electron volts is given by 1 eV = 1.60×10^{-19} J. MeV (mega electron volts) are more commonly used, where 1 MeV = 10^6 eV = 1.6×10^{-13} J.

In the case of ^{235}U, the binding energy in MeV is:

binding energy	$= 2.86 \times 10^{-10} / 1.6 \times 10^{-13}$ MeV
	$= 1.79 \times 10^3$ MeV
binding energy per nucleon	$= 1.79 \times 10^3 / 235$ MeV
	$= 7.62$ MeV

Many different products are possible when uranium-235 undergoes fission. The following equation is typical. It results in the release of about 200 MeV of energy per uranium atom.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{90}_{36}\mathrm{Kr} + 2\,{}^{1}_{0}\mathrm{n}$$

Part 3: Questions

Questions on this worksheet involve calculation of mass defect, binding energy and binding energy per nucleon.

1. Complete the following calculations to find the mass defect, binding energy and binding energy per nucleon of helium.

mass of a neutral helium atom	4.002 604 u
mass of a proton	1.007 276 u
mass of a neutron	1.008 665 u
mass of an electron	0.000 549 u

Start by totalling the individual masses of protons, neutrons and electrons in a neutral helium atom that contains two protons, two neutrons and two electrons.

particle	mass (u) x number =
protons	1.007 276 x 2 =
neutrons	1.008 665 x 2 =
electrons	0.000 549 x 2 =
total mass	=

The mass of the neutral helium atom is: ....

- Calculate the mass defect by subtracting the mass of neutral helium atom from the total mass of the individual particles.

Mass defect (u) = ... – .... = ... u

- Convert the mass defect into kilograms using the conversion factor 1 u = 1.6605×10^{-27} kg.

Mass defect (kg) = ... x (1.6605×10^{-27}) =............................. kg

- Using Einstein's equation $E = m c^2$, convert this mass into binding energy.

Binding energy = ... x $(3.00 \times 10^8)^2$ = ... J

- Helium has four nucleons (two protons and two neutrons). Calculate the binding energy per nucleon.

Binding energy per nucleon = ... J / 4 = ... J per nucleon

- Convert this to MeV per nucleon using the conversion: 1MeV = 1.6×10^{-13} J

For helium:

Binding energy (MeV) = ... / 1.6×10^{-13} = ... MeV

Binding energy per nucleon (MeV) = ... / 4 = ... MeV per nucleon

2. When the nucleus of a uranium-235 atom is divided into two smaller nuclei, mass is converted into energy. Where does this energy originate?

....

....

....

....

3. Boron undergoes fission via thermal neutron capture to produce lithium-7, an alpha particle and energy in the following reaction:

$$n + {}^{10}_{5}B \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He$$

Using the data below, calculate mass defect (in u and kg) and binding energy (in J and MeV) for this reaction.

mass of a neutral boron atom	10.012 939 u
mass of a neutral lithium-7 atom	7.016 005 u
mass of a neutral helium-4 atom	4.002 603 u
mass of a neutron	1.008 665 u

mass defect .... u

mass defect .... kg

binding energy .... J

binding energy .... MeV

4. Thorium-228 undergoes fission according to the equation:

$$^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra} + {}^{4}_{2}\text{He}$$

Use the data below to calculate mass defect and binding energy for this reaction.

mass of a neutral thorium-228 atom	228.028 73 u
mass of a neutral radium-224 atom	224.020 20 u
mass of a neutral helium-4 atom	4.002 60 u
mass of an electron	0.000 55 u

mass defect .... u

mass defect .... kg

binding energy .... J

binding energy .... MeV