Department of
Education

GOVERNMENT OF
WESTERN AUSTRALIA

Year 11 ATAR Physics

Unit 1: Absorbed Dose, Mass/Energy Relationships

Unit 1

Year 11 ATAR Physics Unit 1 2020

Topic: Absorbed Dose, Mass/Energy Relationships

Instructions to Students

This resource package provides students with learning materials for the Physics ATAR Year 11 course. The package focuses on the topic **Absorbed Dose, Mass/Energy Relationships**.

This package is designed to support the program students are completing at their school. If feedback is required when completing this package, students should consult their teacher.

This resource package consists of:

- the **Notes/summary** which provides an explanation of syllabus content concepts. This section is designed to develop the knowledge component of the syllabus
- The **Exercises** which provide an opportunity for students to check their understanding of the content.

It is recommended that students further investigate concepts covered in this resource package by conducting their own research using the text/s they use at school/other resources available or the internet.

Syllabus Points Covered appear in the red boxes.

The measurement of absorbed dose and dose equivalence enables the analysis of health and environmental risks

This includes applying the relationships

Absorbed dose = E/m

Dose equivalent = absorbed dose x quality factor

FALLOUT IN THE FOOD CHAIN – A story of nuclear pollution

At Chernobyl in Russia, on April 25th 1986, there was a nuclear accident in a reactor. When the fission chain reaction ran out of control, some of the radioactive fuel rods exploded. The lid of the reactor blew off due to a rise in power and with white hot fragments of the core. These produced vast quantities of steam resulting in the spread of radioactive debris around the area. This created fires and very high radiation level around the plant. Further chemical explosions occurred as water reacted with zirconium fuel rods to make hydrogen and carbon monoxide.

With the shielding gone, many 'fission products' began to get into the atmosphere. Inert radioactive gases such as xenon-133 were swept high into the atmosphere and were blown north by the wind towards Finland and Sweden. As the cloud passed overhead, they were irradiated by it. Iodine-131 and caesium-137 were other fission products that got into the atmosphere. These were released in the form of fine dust particles or vapour. The radioactive materials rose high into the atmosphere and within five days had been spread over most of Europe, Scandinavia and Britain. The iodine and caesium that fell in the rain produced radioactive hot spots on the ground.

Any vegetation that contains radioactive isotopes can be possibly eaten by sheep or cows and enters the food chain. It appears in milk within a few days and in the meat of the animals after some months. Iodine-131 has a half-life of eight days but still has time to enter our bodies through radioactive milk. Caesium-137 has a half-life of 30 years. It can contaminate vegetation and animals for many years. Reindeer herders of Northern Sweden were hard hit by the fallout. Rain fell over parts of their homeland as the cloud passed and deposited caesium-137 on the lichen that the reindeer eat. Lichen absorbs up to three times as much radiation as other plants. Thousands of reindeer became radioactive from eating the lichen. The farmers' traditional lifestyle and livelihood have been disrupted and will not return to normal until the contaminated lichen has been eaten or has lost its radioactivity. This could take a generation.

NOTE: In December of 2000 the last of the four reactors Chernobyl was closed down and while the chemical explosion at Chernobyl devastated the plant and the area around it, it will do no further damage. The effects of the nuclear explosion however were global and will remain a danger to health for many years to come.

What does all this mean?

Why did the radiation have such an effect? To understand this, it is important to understand the effects of radiation on us and how we can measure it.

Firstly, recall what **ionizing radiation** is. Ionizing radiation is radiation produced when a heavy atom splits or radioactive nuclei release smaller particles to become stable.

If this radiation comes in contact with the cells in your body, it can remove an electron from an atom thus creating a charged ion – hence the name ionizing radiation.

Most forms of nuclear radiation (α, β and γ) are considered to be ionizing radiation, as are X-rays which are high energy, very short wavelength electromagnetic radiation.

There are three main ways to measure the effect of radiation:

1. The *Becquerel* (Bq) measures the activity or the number of decays or disintegrations per second. It gives no indication about the effect of the radiation on biological tissue.
2. The *Gray* (Gy) measures the energy absorbed per kilogram of our body weight but doesn't consider the ionizing effect of the type of radiation we receive.
3. The *Sievert* (Sv) measures not only the amount of radiation per kilogram but also takes into account the ionizing effect of the type of radiation on human tissue. This unit is used when considering radiological protection.

Measurement of Radiation

Activity:

The activity of a radioactive sample is defined as the number of nuclei which decay or disintegrate each second. The unit of activity is the Becquerel (Bq).

1 Bq = 1 decay per second.

Use the relationship: $A = \frac{\Delta N}{\Delta t}$ where: A = activity,

ΔN = number of decays and

Δt = change in time (in seconds)

$$A = A_0\left(\tfrac{1}{2}\right)^n$$

The activity is related to the stability of the radiation source and the half-life (higher activity means less stable and shorter half-life) but little else.

Absorbed Dose:

The absorbed dose is the radiation damage to cells determined by the amount of energy absorbed by the cells.

$$\textit{absorbed dose} = \frac{\textit{energy absorbed (J)}}{\textit{mass of absorbing tissue (kg)}}$$

The S.I. unit for absorbed dose is the GRAY (Gy). 1 Gy = 1 joule of energy absorbed per kilogram.While absorbed dose relates to the amount of energy the cells receive, it doesn't explain the ionizing effect of the radiation and hence the degree of damage to human cells, tissues and organs.

Dose Equivalent:

Dose equivalent is a useful concept when comparing the effects of different amounts of radiation of the same type. For example, 1 Gy of alpha radiation will have a greater effect on the cells than 1 Gy of beta radiation.

Dose equivalent equals the absorbed dose x QF, where QF is a quality factor allowing for different effects of ionising rations on tissues of various kinds.

dose equivalent = absorbed dose x QF

The S.I. unit for dose equivalent is the SIEVERT (Sv).

The table below shows values of QF, you will always be given any required values in assessment tasks.

Radiation type	QF
X-rays, γ-rays and β particles	1
Low energy neutrons	3
High energy neutrons and protons	10
Alpha particles.	20

Exercise 1:

Below are some questions to assist your understanding. Complete Exercise 1 and check your answers at the end of the book.

A laboratory technician accidentally swallows a radioisotope. He records the activity of another sample and finds that there are 1.62 x 10^5 decays per hour. The material swallowed has a long half-life and you can assume therefore that the activity will not change appreciably during the physicist's lifetime. Each decay of the isotope releases 3.60 x 10^{-12} J of energy into the body and that the radioisotope is not eliminated from the body.

a. Calculate the activity of the radioisotope.

b. Calculate the amount of energy absorbed in one year. (1 year = 365 days)

c. If the technician has a mass of 70 kg, calculate the absorbed dose in one year.

d. The technician knows that the sample he swallowed emits alpha particles. Should he be concerned? Explain. (You will need to show calculation of dose equivalent to justify your answer.)

e. A radioactive material has a half-life of 2.45 x 10^{-3} s. What percentage will be left after 1.47 x 10^{-2} s?

Radiation Sources

Radiation strikes our bodies even without nuclear explosions. About 15% is from man-made sources but 85% is from natural radiation which results in a background radiation.

This background radiation is divided into two main groups: **cosmic radiation** from space (about 14% of the radiation we receive) and **terrestrial radiation** from the Earth.

- Terrestrial background radiation can come from the following sources:
  - radon gas (more of a problem for colder climates)
  - fallout from nuclear explosions
  - emissions from nuclear power stations and radioactive waste
  - medical uses – treatment of disease and research
  - use in factories – production lines to check if packets are full or thickness of materials. Also for sterilization of food.
  - use at home – luminous watches, gun sights, exit signs, gas mantles, smoke detectors
  - from the food we eat and from water sources
  - building materials and soil.

Australians receive about 1.5 mSv (1500 μSv) a year and about 50% of this is gamma radiation. This radiation delivers an average dose of 1.9 mJ of energy to each kilogram of our bodies every year and long term. About 2000 people a year may get cancers from its effects. Those in radiation industries (power stations, hospitals) may receive 20 mSv.

Where our radiation comes from
13% - Cosmic rays
37% - Natural radioactivity in the air
0.5% - Nuclear weapons fallout
20% - Ground and buildings
10.4% - Medical
0.5% - Air travel
17% - Food and drink
1.6% Burning coal
0.001% - Nuclear power

Radiation Source	Average annual dose (µSv)	Local variations
Grounds, rocks, air and water	1350	Add 1350 µSv if you live underground Add 1350 µSv if your house is made of granite Take 140 µSv if you live in a weatherboard house
Radioactivity in food and drinks	350	Add 1000 µSv if you have eaten food affected by fallout (e.g. food from Fukushima)
Cosmic radiation	300	Add 200 µSv for each round-the-world flight Add 20 µSv for each 10° of latitude Add 150 µSv if you live 1000m above sea level
Manufactured radiation	60	Add 60 µSv if live near a coal-burning power station Add 30 µSv from nuclear testing in the Pacific
Medical exposure		Add 30 µSv for a chest xray Add 300 µSv for a pelvic xray Add 5000 µSv for a CT scan Add 40 000 000 µSv for a course of radiotherapy using cobalt-60

How radioactive are you? Try the following exercise.

https://www.ansto.gov.au/education/apps#content-how-radioactive-are-you

Physiological Effects of Ionising Radiation

The effect of radiation on our bodies is due to the damage or changes that occur at the cellular level. The magnitude of this effect is proportional to the dose equivalent received.

Symptoms from a large radiation dose to the body become evident within a few days. They include nausea, vomiting and a general 'unwellness' (called radiation sickness).

Some parts of the body are more sensitive to ionising radiation than others, the most sensitive being bone marrow, the reproductive organs, the eyes, digestive system and circulatory system.

Lower doses of radiation may produce effects which only become apparent after several months or even years. These include a reduced life expectancy, the development of leukaemia or tumours and cataracts on the eye lens.

Genetic damage, if it occurs, may not be apparent for several generations. The table below gives some physiological effects of ionising radiation.

Approximate Dose Equivalent (Sv)		Effects
<0.25	(250 mSv or 250 000 µSv)	no observable effects
0.5	(500 mSv or 500 000 µSv)	slight temporary blood changes
1.0	(1000 mSv or 1 000 000 µSv)	nausea, fatigue, vomiting
2.0-2.5	(2000 mSv or 2 000 000 µSv)	fatality possible
5.0	(5000 mSv or 5 000 000 µSv)	about 50% of victims die
10.0	(1 0000 mSv or 10 000 000 µSv)	all victims die

An annual dose of 1.5 mSv (1500 µSv) of background radiation will have no visible effect.

Safety and Shielding

Radioactive material must be handled with care. The greatest danger is from ingestion. Don't touch sources without gloves or point them at the body, handle radioactive material with tongs held at arm's length.

Always keep in lead-lined boxes when not in use. Remember, do not take risks with this invisible radiation, the damage it causes many not show up for several years, or until you have children. Shielding is an important way to protect yourself.

The underlying principles of radiation protection from external sources is known as the TDS Rules:

- decrease **T**ime of exposure
- increase **D**istance from source
- use **S**hielding where necessary.

Einstein's mass/energy relationship relates the binding energy of a nucleus to its mass defect

This includes applying the relationship $\Delta E = \Delta m c^2$

Atomic Mass Unit

To enable us to do calculations about mass and energy in nuclear processes, we need to define a new unit.

In SI units, mass is in kilograms and energy in joules but because of the very small values associated with the atom, we use atomic mass units (amu or u for short) for mass and electron volts (eV or MeV) for energy.

Atomic Mass Unit:

One atomic mass unit, u, is the mass of 1/12th of carbon-12.

1 u is equal to 1.6606×10^{-27} kg. The table shows the mass of the particles in the atom.

PARTICLE	ATOMIC MASS (u)
electron	0.00055
Proton	1.00728
Neutron	1.00867

Electron Volt:

An electron volt is a unit of energy.

It can be thought of as the energy that an electron would gain when it moves through a potential difference of 1 volt – hence *one electron volt*.

One electron volt (eV) is equal to 1.60×10^{-19} J. $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$

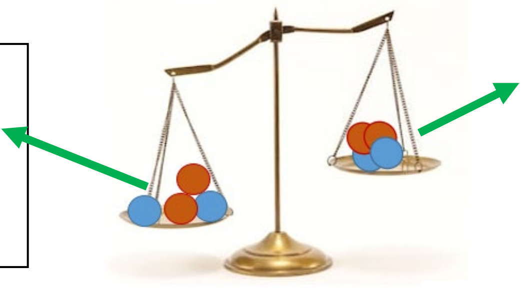
It is common to use mega-electron volts (MeV) for nuclear process which is 1.60×10^{-13} J. ($1.60 \times 10^{-19} \times 10^{6}$) $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$

One atomic mass unit, u, also equals 931 mega-electron volts. 1u = 931 MeV. This relationship is used when matter is converted into energy.

Mass Defect and Binding Energy

If the individual masses of protons and neutrons in an atom were added together, they would be greater than the actual mass of the atom.

Nucleons
Mass of protons = 2 x 1.00728 u
= 2.01456 u
Mass of neutrons = 2 x 1.00866 u
= 2.001732 u
Total mass = 4.03188 u

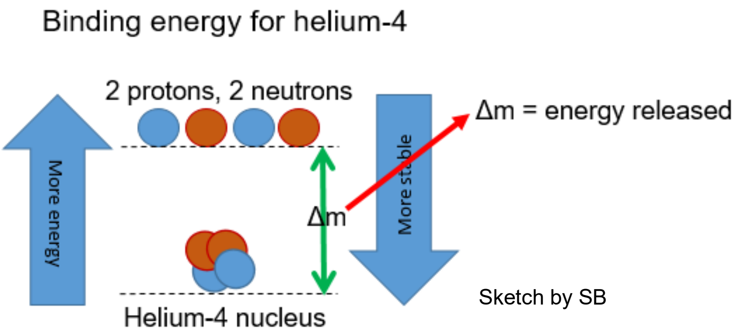


Nucleus
Mass of helium-4 =
4.0001505 u

Image: free to use stocksnap.io and SB

When the parts of a nucleus come together, some of the mass is converted to energy to hold the nucleus together.

This energy comes from the conversion of mass into energy when protons and neutrons combine and is called the **binding energy.**



Sketch by SB

This is the energy that must be put into a nucleus in order to break it into its components.

If the nucleus is pulled apart, the individual particles will weigh less. The missing mass in converted into energy (heat and light).

binding energy = mass defect x (speed of light)^2.

This mass difference between the “mass of the individual protons and neutrons” and the “mass of the nucleus itself” is called the **mass defect**, **md.**

mass defect = (mass of neutrons and protons) - (mass of nucleus)

so combining these two ideas,

$E = m c^2$ where: E = the binding energy in joules (J)
m = mass defect in kg.
c = speed of light, 3.0×10^8 ms^{-1}

NOTE: When doing calculations, masses are usually given in u, but sometimes they are given in kg. Energy is often required in eV or MeV or sometimes in J. Read the question carefully.

FOR A SINGLE ATOM

Example: Calculate the binding energy of a lithium-7 nucleus, ${}^{7}_{3}\mathrm{Li}$ in joules and MeV.
Two methods can be used depending on the question. Each requires the mass defect.

mass defect = (mass of neutrons and protons) - (mass of nucleus)
md = [(3 x mass proton) + (4 x mass neutron)] - (mass of ${}^{7}_{3}\mathrm{Li}$)

$$= [(3 \times 1.6726 \times 10^{-27}) + (4 \times 1.6750 \times 10^{-27})] - 1.1647 \times 10^{-26}$$
$$= 5.0178 \times 10^{-27} + 6.7000 \times 10^{-27} - 1.1647 \times 10^{-26}$$
$$= 7.080 \times 10^{-29} \text{ kg}$$

Finding energy in Joules	**Finding energy in MeV**
binding energy per nucleus, $E = m c^2$ $E = 7.080 \times 10^{-29} \times (3 \times 10^8)^2$ **$E = 6.372 \times 10^{-12}$ J** 1 MeV = 1.6×10^{-13} J x MeV = 6.372×10^{-12} J x = **39.8 MeV**	1.66×10^{-27} kg = 1 u so mass in u = $\frac{7.080 \times 10^{-29}}{1.66 \times 10^{-27}}$ u = 0.04265 u 1u = 931 MeV Therefore MeV = 0.04265 x 931 **= 39.7 MeV**

FOR AN EQUATION

NOTE:

*When dealing with a nuclear reaction, **DO NOT** convert the atoms in the equation into individual protons and neutrons as the individual protons and neutrons have a GREATER mass than the atom.*

Example: In the sun, hydrogen atoms combine to make helium in the process of fusion. In this process, energy is released. One of the reactions is shown. ${}^{1}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He}$ Determine the binding energy release for this reaction in joules and MeV.

ANSWER: Use the total mass of the LHS subtract the total mass of the RHS using the masses given for each atom (not the masses of individual protons and neutrons).

mass defect **=** mass of the reactants – mass of the products

${}^{1}_{1}\text{H} = 1.6736 \times 10^{-27}$ kg

${}^{2}_{1}\text{H} = 3.3446 \times 10^{-27}$ kg

${}^{3}_{2}\text{He} = 5.0084 \times 10^{-27}$ kg

$$\begin{aligned} m &= (\text{mass } {}^{1}_{1}\text{H} + {}^{2}_{1}\text{H}) - (\text{mass } {}^{3}_{2}\text{He}) \\ &= (1.674 \times 10^{-27} + 3.345 \times 10^{-27}) - 5.008 \times 10^{-27} \\ &= 9.800 \times 10^{-30} \text{ kg} \end{aligned}$$

In joules:

$$\begin{aligned} E &= md \times c^2 \\ &= 9.800 \times 10^{-30} \times (3.0 \times 10^{8})^2 \\ \mathbf{E} &= \mathbf{8.82 \times 10^{-13}\ J} \end{aligned}$$

In MeV

$$\text{mass in u} = \frac{9.800 \times 10^{-30}}{1.6606 \times 10^{-27}} = 0.005901 \text{ u}$$

$$\begin{aligned} \text{MeV} &= 0.005901 \times 931 \\ &= \mathbf{5.49\ MeV} \end{aligned}$$

Exercise 2:

Below are some questions to assist your understanding. Complete Exercise 2 and check your answers at the end of the book.

Complete the following question using both methods.

A common reaction in nuclear fission power plants is ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3{}^{1}_{0}\text{n}$, calculate the energy released from this reaction in joules and MeV.

${}^{235}_{92}\text{U} = 3.902 \times 10^{-25}$ kg

${}^{141}_{56}\text{Ba} = 2.339 \times 10^{-25}$ kg

${}^{92}_{36}\text{Kr} = 1.526 \times 10^{-25}$ kg

${}^{1}_{0}n = 1.674 \times 10^{-27}$ kg

Binding Energy per Nucleon

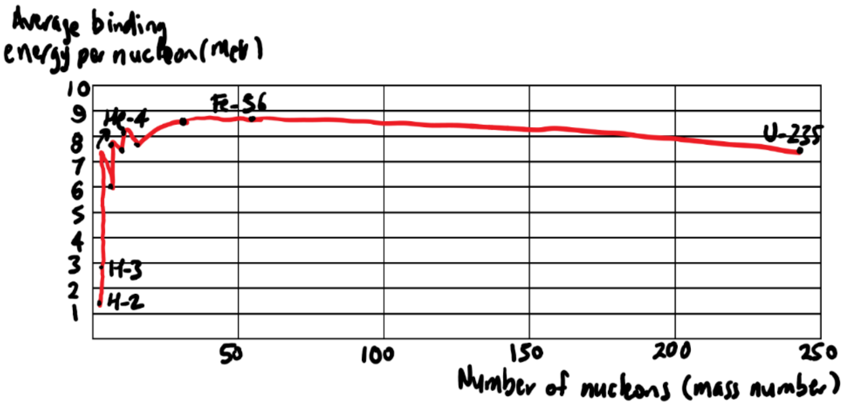
A more useful measure of stability is the binding energy per nucleon. This explains how much energy must be applied to remove each nucleon from the rest of the nucleus.

Binding energy per nucleon of an atom is the binding energy of that atom divided by the total number of protons and neutrons.

For the example of binding energy for lithium-7, the **binding energy per nucleon** = **39.7 ÷ 7 = 5.67 MeV per nucleon.**

If the binding energy per nucleon is high, the nucleus is stable and difficult to pull apart. Atoms with mass numbers close to 60 have the highest binding energy per nucleon as shown in the graph. Uranium will often undergo fission into two roughly similar daughter products.

Helium, on the other hand, has a high binding energy per nucleon and is very stable, which helps to explain why alpha particles are emitted when large atoms break up as the bonds between the helium nucleons are very strong.



Sketch by SB

In **fission**, energy is released when a larger, more unstable atom decays to a smaller atom/s often emitting radiation (explained later).

In nuclear **fusion**, two smaller atoms come together to make a larger atom. As this is the opposite of nuclear fission, it may seem unusual that energy is released.

Again, this relates to the binding energy per nucleon. If the new atom in fusion has a higher binding energy than the two atoms which joined, energy will be released.

Atomic mass units (amu or u)

An atomic mass unit (amu or u) is a unit of mass used to express atomic and molecular weights, equal to one twelfth of the mass of an atom of carbon-12.

It is often more convenient to perform calculations using amu.

Exercise 3:

Below are some questions to assist your understanding. Complete Exercise 3 and check your answers at the end of the book.

In a nuclear fission power plants $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$,
Calculate the energy released from this reaction in joules and MeV.

$^{235}_{92}U$ = 235.04393 u
$^{141}_{56}Ba$ = 140.91441 u
$^{92}_{36}Kr$ = 91.92616 u
$^{1}_{0}n$ = 1.00867 u

a. determine the mass defect in amu.
b. convert the mass defect in amu to kg – 1 u = 1.6606 x 10^{-27} kg.
c. find the energy in J – $E = mc^2$.
d. convert J to eV – 1 MeV = 1.6 x 10^{-13} J.

Alternatively:

e. mass defect in amu.
f. convert amu to MeV – 1u = 931 MeV.
g. convert MeV to J – 1 MeV = 1.6 x 10^{-13} J.

Exercise 4:

Below are some questions to assist your understanding. Complete Exercise 4 and check your answers at the end of the book.

Binding Energy Problems
Use the atomic masses in the table below.

Isotope	Atomic mass (u)	Isotope	Atomic mass (u)
Neutron	1.00867	Oxygen-17	16.99913
Proton	1.00728	Krypton-92	91.92616
Hydrogen-1	1.00783	Iodine-131	130.90613
Hydrogen-2	2.01355	Barium-141	140.91441
Hydrogen-3	3.01605	Xenon-142	141.92971
Helium-3	3.01603	Gold-198	197.96824
Helium-4	4.00260	Mercury-198	197.96677
Lithium-7	7.01601	Thorium-234	234.04360
Carbon-12	12.00000	Uranium-235	235.04393
Carbon-14	14.00324	Uranium-238	238.05079
Nitrogen-14	14.00307	Plutonium-239	239.05216
Oxgyen-16	15.99943		

1. What is the binding energy per nucleon in MeV for the following atoms involved in nuclear energy:
   a. U-238 nucleus
   b. He-4 nucleus
   c. Fe-56 (one of the most stable atoms) (Fe = 55.934939 u)
2. The oxygen atom ${}^{16}_{8}O$ has an isotope, ${}^{17}_{8}O$. Find the binding energy of each nucleus and thus; determine which is more stable.
3. Calculate the energy released from one decay of U-238. ${}^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th$
4. There are about 6.023 x 10^{23} atoms in 235 g of pure uranium-235. The bomb dropped on Hiroshima had approximately twice this mass of uranium-235.
   a. Calculate the energy release for one atom of U-235 in joules and MeV
   b. How much energy was released by the Hiroshima bomb in joules and MeV?
5. H-3 and H-2 will fuse to form He-4 and one neutron.
   a. Work out the mass defect.
   b. How much energy will one fusion reaction release in joules and MeV?
   c. The energy released from one fission reaction of U-235 is about 200 MeV. How does this compare with the energy released in a fusion reaction?
6. What is the binding energy per nucleon in MeV for the following atoms involved in nuclear energy:
   a. U-238 nucleus
   b. He-4 nucleus
   c. Fe-56 (the most stable isotope) (Fe = 55.934939 u)
7. The oxygen atom ${}^{16}_{8}O$ has an isotope, ${}^{17}_{8}O$. Find the binding energy of each nucleus and thus; determine which is more stable.
8. Calculate the energy released from one decay of U-238. ${}^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th$

Alpha and beta decay are examples of spontaneous transmutation reactions, while artificial transmutation is a managed process that changes one nuclide into another.

Transmutation of Isotopes and Decay Series

When a nucleus emits a particle such as an alpha or beta particle, the number of protons can change and a new element is formed. This is called ***transmutation*** – alpha removes two protons and beta minus results in an increase of one proton. (beta plus decay results in a decrease of one proton.)

Transmutations can be natural, for example radioactive decay of uranium, or artificial, for example: bombarding nucleus with alpha or beta particles, or with neutrons.

Sometimes the new element is also unstable, and it decays. This can create a ***decay series***.

The original source is called the ***parent*** and the new products are called the ***daughter*** products.

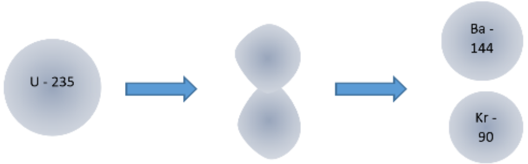
Neutron-induced nuclear fission is a reaction in which a heavy nuclide captures a neutron and then splits into smaller radioactive nuclides with the release of energy.

Fission and Fusion

Nuclear Fission:

Fission is the splitting of the nucleus of an atom to produce two relatively equal daughter products together with a large amount of energy. One possible reaction is:

A slight disturbance has little effect on the U – 235 nucleus.



A large disturbance, like neutron bombardment, can cause the U – 235 nucleus to split into two.

Sketch by SB

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\ {}^{1}_{0}n \quad (\sim 200 \text{ MeV or } \sim 3.2 \times 10^{-11} \text{ J}) $$

There are millions of atoms in one kilogram of uranium-235 which could theoretically produce about 8 x 10^{13} J of energy.The reaction above needs a neutron to start it but it then produces 3 neutrons. Hence, one reaction can cause several more reactions leading to a self-sustaining series of reactions called a chain reaction.

Nuclear fusion is a reaction in which light nuclides combine to form a heavier nuclide, with the release of energy.

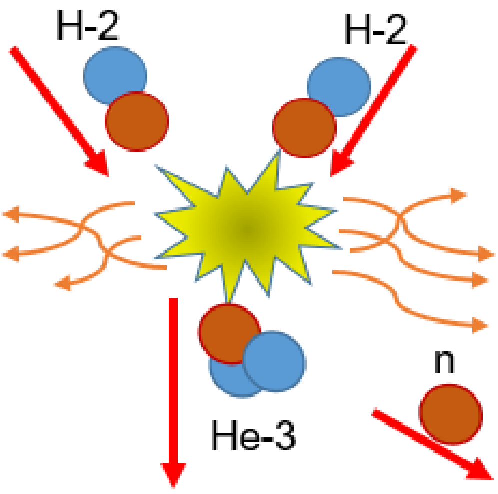
Nuclear Fusion:

Fusion involves the joining of two light atomic nuclei to form one heavier nucleus.

This process also produces a large amount of energy as is shown by the energy produced from our sun and other stars. A typical reaction in our sun is shown below:

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$$

This reaction releases about 1.6 x 10^{14} J per kilogram of helium produced. The products of the reaction are safe for humans and the environment unlike nuclear fission.



Sketch by SB

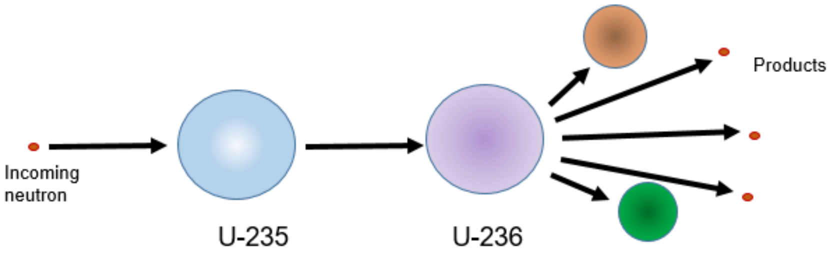
Fusion reactors are currently not possible due to the high temperatures needed (100 million ^{0}C), the ability to confine a sufficient quantity of the reacting nuclei to release useful energy and the fact that the heated gas is in a state of matter called plasma, which cannot be contained by ordinary materials, only within a strong magnetic field. Research into fusion reactors is ongoing.

A fission chain reaction is a self-sustaining process that may be controlled to produce thermal energy, or uncontrolled to release energy explosively if its critical mass is exceeded.

Chain Reactions and Critical Mass Configuration

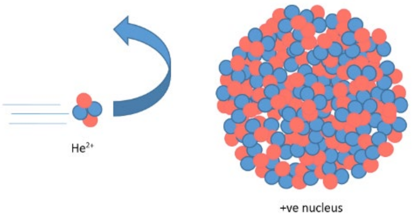
A Neutron Induced Chain Reaction

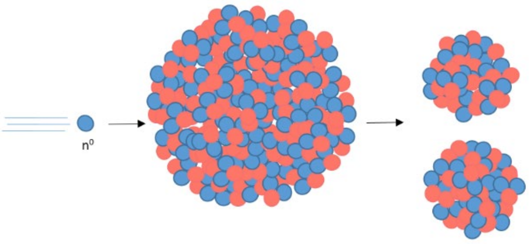
Fission is the splitting of an atom into smaller parts with the release of neutrons, as is shown below.



Sketch by SB

Positively charged particles would be repelled by a nucleus while uncharged neutrons are able to smash into the nucleus.

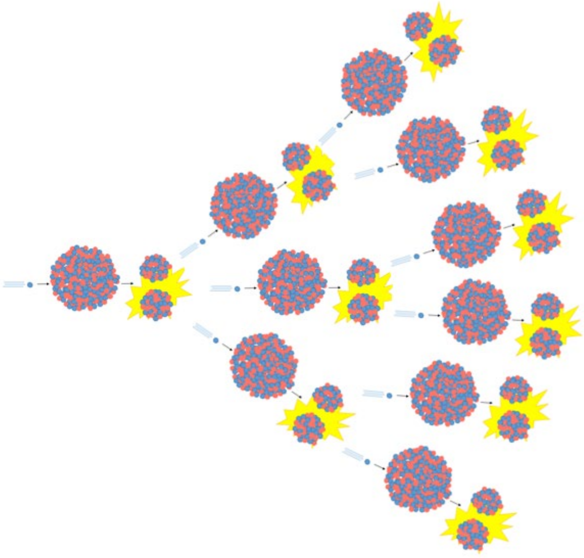




Sketch by SB

The neutrons released during fission can in turn cause further fission reactions, as the released neutrons collide with other U-235 nuclei.

If on average, two of these released neutrons were to cause further fissions, then the number of fission events would increase as the series 1, 2, 4, 8, 16, 32, 64, …… a runaway explosion!



Sketch by SB

This is known as a self-sustaining neutron induced chain reaction.
Fortunately, such a chain reaction does not easily occur due to a variety of factors:

a. Neutrons may simply escape from the material without hitting any nuclei. Remember, nuclei are an extremely small part of an atom.

b. Neutrons may be absorbed by uranium-238 nuclei (rarely undergoes fission). Only 0.7% of naturally occurring uranium is the fissile uranium-235.

c. Only the very slow neutrons, called thermal neutrons, are likely to cause uranium-235 to split. Fast neutrons emitted from a fission reaction do not interact with uranium-238.

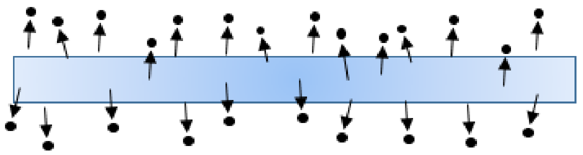
In a nuclear reactor, this chain reaction is controlled as neutrons are absorbed by control rods rather than U-235 and no explosion occurs, rather the energy produced is converted to electrical energy to run the country. 75% of France’s energy comes from nuclear reactors.

Critical Mass Configuration

Critical mass refers to the mass of fissile material required to sustain an ***uncontrolled chain reaction*** such as that which occurs in an atom bomb.

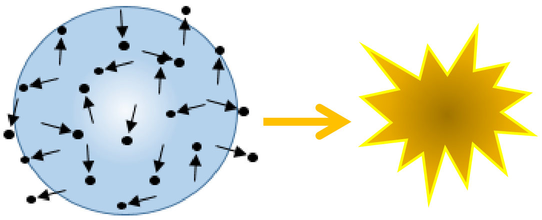
If too little matter is present, most of the neutrons produced in a fission reaction escape from the material without interaction.

Critical mass depends on the percentage of U-235 in a sample since uranium-238 is not fissile. It also depends on the shape of the mass.



20 kg slab of U-235: **subcritical**.

Neutrons can escape without reacting.



20 kg sphere of U-235: **supercritical**.

Sketch by SB

Less neutrons can escape, more cause reactions.

For pure U-235, critical mass is only a few kilograms, while for 3% enriched uranium it is several tonnes (enriched uranium is mainly U-238 with U-235 added ie 3% enriched uranium has 3% U-235.)

Nuclear Reactors

General elements of the Design of a Nuclear Reactor

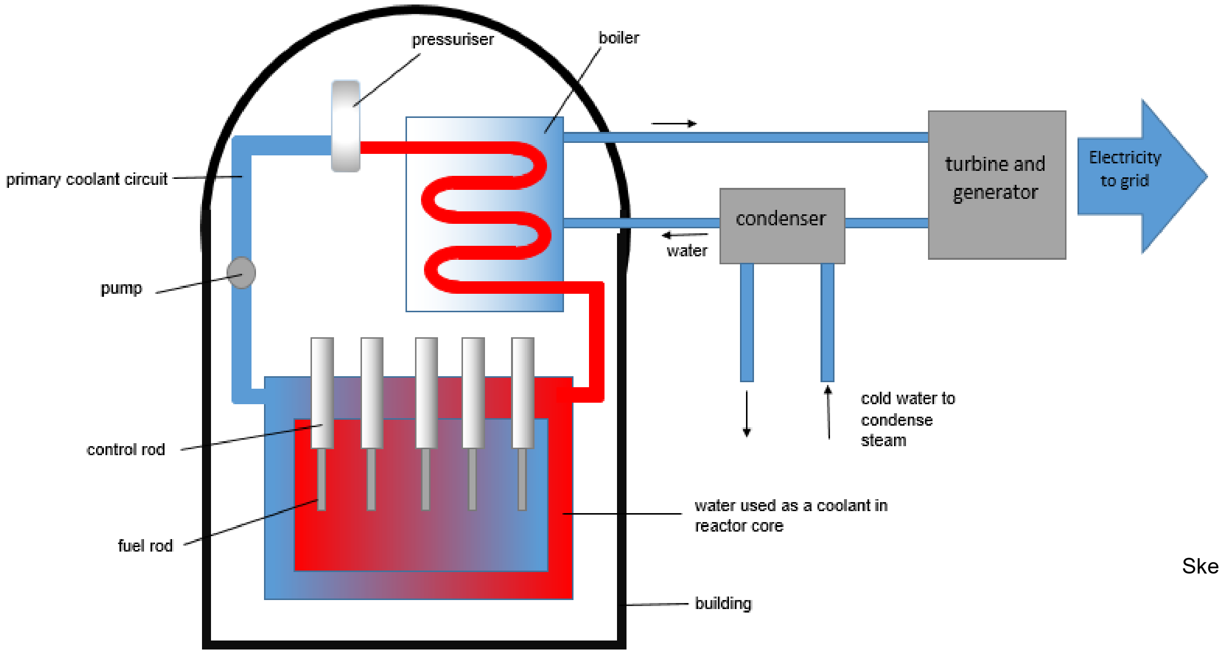
- Fuel rods – these long, thin rods contain the pellets of enriched uranium for fission. Enriched U-235 is used to allow a sustained chain reaction.

- Moderator – this is a material that slows the neutrons to help promote fission. Fission reactions are more likely to occur when the neutron is slow moving.

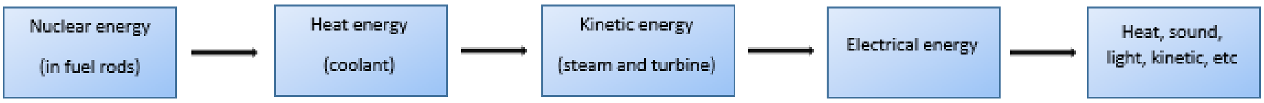
- Control rods – these are a material that absorb neutrons and control the fission reaction. Without them the reaction will become uncontrollable and an explosion will occur.

- Radiation shielding – fission reactions produce gamma radiation so the reactor core needs shielding to protect the workers.

- Coolant – fission reactions produce a large amount of energy, so a coolant is needed to remove this heat energy.



Sketch by SB



The energy from the coolant is then passed to pipes containing water. The water is converted into steam and this steam is used to rotate the turbines which drive generators. The generators produce electricity for use in industry or homes.

This is not unlike the production of electricity from fossil fuels where the heat energy from burning the fossil fuels is used to turn water to steam to rotate turbines.

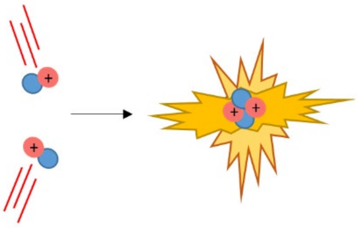
Advantages and Disadvantages of Nuclear Energy

Advantages:	Disadvantages:
1. Nuclear power is a more practical, reliable, economical, cheaper energy and a safe way of energy production.	1. The Reactor has to be constantly cooled.
2. The Earth has limited supplies of coal and oil. Nuclear power plants could still produce electricity after coal and oil became scarce.	2. Workers have a risk of exposure to excessive radiation.
3. Nuclear power plants need less fuel than those that burn fossil fuels. One tonne of uranium produces more energy than is produced by several million tonnes of coal or several million barrels of oil.	3. Nuclear reactors also have waste disposal problems. Reactors produce nuclear waste products which emit dangerous radiation.
4. Coal and oil burning plants pollute the air. Well-operated nuclear power plants do not release contaminants into the environment.	4. The waste products cannot be thrown away like ordinary garbage.
5. A small amount of uranium produces a vast amount of energy.	5. For some isotopes it requires thousands of years for materials to no longer radiate.
6. It doesn't produce CO_2 like fossil fuels.	6. The nuclear radiation harms the cells of the body which can make people sick or even kill them.
7. Waste is minimal.	7. One possible type of reactor disaster is known as a **meltdown**. In such an accident, the fission reaction goes out of control, leading to a nuclear explosion and the emission of huge amounts of radiation.

The management of any nuclear wastes must be based on the knowledge of the behaviour of radiation.

More energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy.

Fusion



When two isotopes of hydrogen fuse to form a helium nucleus, energy is released.

Image by SB

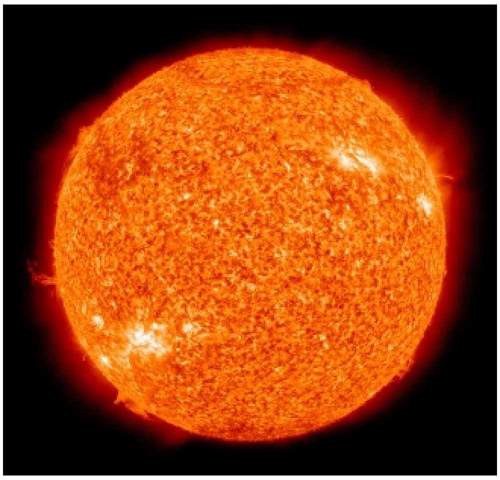
The binding energy of the nucleus appears as a loss in mass, Δm which can be calculated using $\Delta E = \Delta mc^2$.

stocksnap.io and SB

The Sun – A Natural Fusion Reactor

Nuclear fusion is the ultimate source of the solar energy we receive every day from the Sun.

Within the sun, smaller atoms and molecules are progressively being fused to form larger molecules with the release of large amount of energy.



pixabay.com

Slow moving nuclei do not have enough energy to fuse – they are repelled by their positive charges.

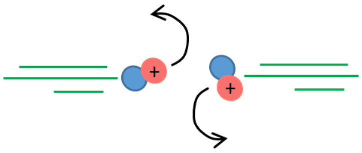


Image by SB

At very high temperatures, nuclei can get close enough to overcome the repulsive forces and the strong nuclear forces comes into effect, allowing the nuclei to fuse.

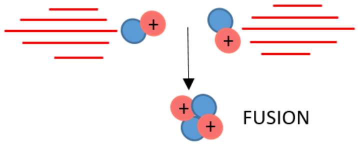


Image by SB

One reaction within the Sun involves the fusing of two isotopes of hydrogen, deuterium (H-2) and tritium (H-3) to produce Helium (He-4) and a neutron.

The difference in the mass between the reactants and the products is converted to solar energy (E = mc^2) which is the source of nearly all energy on Earth.

Nuclear fusion could be described as the ultimate energy source for mankind as deuterium, the fuel for nuclear fusion, is readily obtained from sea water. Tritium can be obtained by irradiating lithium metal in a nuclear reactor.

A great deal of energy is produced during fusion however the radioactive waste is very small. While commercial nuclear fusion reactors are still some way off, it is likely they will become commonplace next century.

Exercise 5:

Below are some questions to assist your understanding. Complete Exercise 5 and check your answers at the end of the book.

Fusion

1. Calculate the energy released from one reaction in the sun. (in joules and MeV)
   H-2 + H-3 produces He-4 and a neutron.

2. There are roughly 1 x 10^{57} particles in the Sun of which one quarter are helium atoms. Calculate the amount of energy released (in joules) in creating these helium atoms assuming, for this exercise only, all came from the reaction discussed above.

Answers to Exercises

Exercise 1:

a. Activity = $1.62 \times 10^5 \div (60 \times 60) = 45.0$ Bq

b. Energy = $3.6 \times 10^{-12} \times 45 \times 365 \times 24 \times 60 \times 60 = 5.11 \times 10^{-3}$ J

c. absorbed dose = $5.11 \times 10^{-3} \div 70 = 7.30 \times 10^{-5}$ Gy

d. Dose = $7.29833 \times 10^{-5} \times 20 = 1.46 \times 10^{-3}$ Sv
= 1.46 mSv
less than background radiation

e. A radioactive material has a half-life of 2.45×10^{-3} s. What percentage will be left after 1.47×10^{-2} s?

$$n = \frac{t}{t_{1/2}} = \frac{1.47 \; x \; 10^{-2}}{2.45 \; x \; 10^{-3}} = 6 \qquad A = A_0 \, (0.5)^n = 100 \, (0.5)^6 = 1.56 \,\%$$

Exercise 2:

$m_d = ({}^{235}_{92}U + {}^{1}_{0}n) - ({}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n)$
$= (3.902 \times 10^{-25} + 1.674 \times 10^{-27}$ kg$) - (2.339 \times 10^{-25} + 1.526 \times 10^{-25} + [3 \times 1.674 \times 10^{-27}])$
$= 3.52 \times 10^{-28}$ kg

md in u $= \dfrac{3.52x10^{-28}}{1.66x10^{-27}} = 0.212$ u

MeV = 0.212×931
= 197 MeV
= $197 \times 1.60 \times 10^{-13}$
= 3.15×10^{-11} J

Exercise 3:

a. md = $({}^{235}_{92}U + {}^{1}_{0}n) - ({}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n)$
= (235.04393 + 1.00867) – (140.91441 + 91.92616 + 3 x 1.00867) = 0.18602 u

b. md = $0.18602 \times 1.6606 \times 10^{-27} = 3.08905 \times 10^{-28}$ kg

c. $E = mc^2 = (3.08905 \times 10^{-28}) \times (3 \times 10^8)^2 = 2.7801 \times 10^{-11}$ J

d. $E = \dfrac{2.7801 \; x \; 10^{-11}}{1.6 \; x \; 10^{-13}} = 174$ MeV

e. md = 0.18602 amu

f. E = 0.18602 x 931 = 173 MeV

g. $E = 173.18 \times 1.6 \times 10^{-13} = 2.77 \times 10^{-11}$ J

Exercise 4: Binding Energy Problems

1.
   a. U-238 = 92p + 146n
      md = ([92 x 1.00728) + (146 x 1.00867)] - U-238
      = 92.66976 + 147.26582 – 238.05079
      = 1.88479 u
      E = 1.88479 x 931
      = 1754.739 MeV per atom
      as there are 238 nucleons, then
      binding energy per nucleon $= \dfrac{1754.739}{238} = 7.37$ MeV

b. He-4 = 2p + 2n
m = (2 x 1.00728) + (2 x 1.00867) – 4.00260
= 0.0293 u

E = 0.0293 x 931
= 27.2783 MeV per atom
as there are 4 nucleons, then
binding energy per nucleon = $\frac{27.2783}{4}$ = 6.82 MeV

c. Fe-56 = 26p + 30n
= (26 x 1.00728) + (30 x 1.00867) – 55.934939
= 0.514441u
E = 0.514441 x 931
= 478.9445 MeV per atom
as there are 56 nucleons, then
binding energy per nucleon = $\frac{478.9445}{56}$ = 8.55 MeV

2. O-16 = 8p + 8n
= (8 x 1.00728) + (8 x 1.00867) – 15.99943
= 0.12817 u
E = 0.12817 x 931
= 119.32627 MeV per atom
as there are 16 nucleons, then
binding energy per nucleon = $\frac{119.32627}{16}$ = 7.46 MeV

O-17 = 8p + 9n
= (8 x 1.00728) + (9 x 1.00867) – 16.99913
= 0.13714 u

E = 0.13714 x 931
= 127.67734 MeV per atom
as there are 17 nucleons, then
binding energy per nucleon = $\frac{127.67734}{17}$ = 7.51 MeV
Oxygen 17 has the greater binding energy so is more stable.

3. md = 238.05079 – (4.00260 + 234.04360)
= 4.59 x 10^{-3} u
= 7.622154 x 10^{-30} kg

E = mc^2
= 7.622154 x 10^{-30} x $(3 \times 10^8)^2$
= 6.86 x 10^{-13} J or E = $\frac{\mathbf{6.86x10^{-13}}}{\mathbf{1.6x10^{-13}}}$ = 4.29 MeV or E = 4.59 x 10^{-3} x 931 = 4.27 MeV

4.

a. U-235 = (92p + 143n) - 235.04393

md = ([92 x 1.00728) + (143 x 1.00867)] - 235.04393
= 92.66976 + 144.23981 - 235.04393
= 1.865577 u
= 3.09686×10^{-27}

E = $3.09686 \times 10^{-27} \times (3 \times 10^{8})^{2}$
= <u>2.79×10^{-10} J per atom</u>

E = 1.865577 x 931
= 1736.852 MeV
= <u>1.74×10^{3} MeV per atom</u>

b. E = $2.78717 \times 10^{-10} \times 6.023 \times 10^{23} \times 2$
= 3.36×10^{14} J

and

E = $1736.852 \times 6.023 \times 10^{23} \times 2$
= 2.09×10^{27} MeV

5.

a. md = (2.01355 + 3.01605) - (4.00260 + 1.00867)
= 0.01833 u

b. E = $0.01833 \times 1.66 \times 10^{-27} \times (3 \times 10^{8})^{2}$
= 2.74×10^{-12} J

E = 0.01833 x 931
= 17.1 MeV

c. The energy from U-235 is much greater

6. What is the binding energy per nucleon in MeV for the following atoms involved in nuclear energy:

a. U-238 nucleus

U-238 = 92p + 146n
md = ([92 x 1.00728) + (146 x 1.00867)] - U-238
= 92.66976 + 147.26582 – 238.05079
= 1.88479 u
E = 1.88479 x 931
= 1754.739 MeV per atom
as there are 238 nucleons, then

binding energy per nucleon = $\frac{1754.739}{238}$ = 7.37 MeV

b. He-4 nucleus

He-4 = 2p + 2n
m = (2 x 1.00728) + (2 x 1.00867) – 4.00260
= 0.0293 u
E = 0.0293 x 931
= 27.2783 MeV per atom
as there are 4 nucleons, then

binding energy per nucleon = $\frac{27.2783}{4}$ = 6.82 MeV

c. Fe-56 (one of the most stable atoms) (Fe = 55.934939 u)

Fe-56 = 26p + 30n
= (26 x 1.00728) + (30 x 1.00867) – 55.934939
= 0.514441 u
E = 0.514441 x 931
= 478.9445 MeV per atom

as there are 56 nucleons, then

binding energy per nucleon = $\frac{478.9445}{56}$ = 8.55 MeV

You will notice that the binding energy per nucleon is greater than the previous two examples.

7. The oxygen atom ${}^{16}_{8}\mathrm{O}$ has an isotope, ${}^{17}_{8}\mathrm{O}$. Find the binding energy of each nucleus and thus determine which is more stable.

O-16 = 8p + 8n
= (8 x 1.00728) + (8 x 1.00867) – 15.99943
= 0.12817 u
E = 0.12817 x 931
= 119.32627 MeV per atom
as there are 16 nucleons, then

binding energy per nucleon = $\frac{119.32627}{16}$ = 7.46 MeV

O-17 = 8p + 9n
= (8 x 1.00728) + (9 x 1.00867) – 16.99913
= 0.13714 u
E = 0.13714 x 931
= 127.67734 MeV per atom
as there are 17 nucleons, then

binding energy per nucleon = $\frac{127.67734}{17}$ = 7.51 MeV

Oxygen 17 has the greater binding energy so is more stable.

8. Calculate the energy released from one decay of U-238. ${}^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}$

md = 238.05079 – (4.00260 + 234.04360)
= 4.59×10^{-3} u
= 7.622154×10^{-30} kg
$E = mc^2$
= $7.622154 \times 10^{-30} \times (3 \times 10^8)^2$
= 6.86×10^{-13} J or E = $\frac{6.86\mathrm{x}10^{-13}}{1.6\mathrm{x}10^{-13}}$ = 4.29 MeV or E = $4.59 \times 10^{-3} \times 931$ = 4.27 MeV

Exercise 5: Fusion

1. md = (2.01355 + 3.01605) – (4.00260 + 1.00867)
= 0.01833 u
= $0.01833 \times 1.6606 \times 10^{-27}$
= 3.04388×10^{-29} kg

$E = mc^2$ and MeV = $\frac{2.734x10^{-12}}{1.6x10^{-13}}$

= $3.04388 \times 10^{-29} \times (3 \times 10^8)^2$
= 2.734×10^{-12} J = 17.1 MeV

Or E = 0.01833 x 931
= 17.1 MeV

2. energy = $1 \times 10^{57} \times 0.25 \times 2.734 \times 10^{-12}$
= 6.84×10^{44} J