INTRODUCTION

Nuclear radiation is radiation emitted from the nucleus of an atom. There are many types of nuclear radiation, some that we experience every day and are harmless, and others that can have lasting effects.

Nuclear physics is a topic of great public interest and public fear. Public phobia about anything *nuclear* or anything *radioactive* is likened to the similar fears provoked by the advent of electricity and petrol powered vehicles some 100 years ago. Just as fears of electricity in homes and petrol in cars stemmed from ignorance, many of today's fears, about anything nuclear stems from a lack of knowledge about the nucleus and its processes.

Knowledge of the atomic nucleus began with the chance discovery of radioactivity in 1895 by Wilhelm Roentgen. He called this new type of ray, **X rays** – rays of unknown nature.

X rays pass more readily through flesh than through bone and produce an image on a film.

Today we know that X-rays are high-frequency electromagnetic waves, usually emitted by the de-excitation of the innermost orbital electrons of atoms.

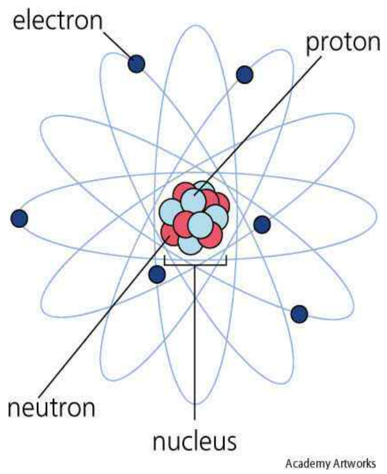
Two months after Roentgen announced his discoveries Antoine Henri Becquerel tried to find out if other elements emitted X-rays. He discovered that Uranium produced rays. It was soon discovered that other elements (thorium, actinium and two new elements discovered by Marie and Pierre Curie-polonium and radium) also emitted similar rays.

The emission of these rays was evidence of much more drastic changes in the atom than atomic excitation. These rays were the result of changes occurring within the central atomic core – the nucleus.

For a timeline of nuclear discoveries, refer to pages 100-101 in the textbook.

A MODEL FOR THE STRUCTURE OF THE ATOM

The current understanding of the structure of an atom was first devised by Ernest Rutherford in 1911.



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The **nucleus** is at the centre of the atom and occupies 10^{-12} of the volume of the atom, yet it contains over 99% of its mass. Nuclear radii are of the order 10^{-15} m. The nucleus is positively charged and is made up of at least two types of particles, **protons** (positively charged) and **neutrons** (electrically neutral), collectively known as **nucleons**. Both protons and neutrons are part of a family known as **hadrons**. There are also many other types (~70) of hadrons.
The nucleus is held together by what is known as the **strong nuclear force**. The nucleus is surrounded by a cloud of negatively charged **electrons**, which move about the nucleus is definite energy states. Just as there are energy levels for the orbital electrons of an atom, there are energy levels within the nucleus.

Atomic number and mass number

The **atomic number** is the number of protons in an atom. Every atom has the same number of protons and electrons, because they need to be electrically neutral.

The electrons in an atom have almost no mass. So the mass of an atom is nearly all due to its protons and neutrons. The **mass number** = the number of protons and neutrons in an atom.

Shorthand for an atom

Mass number

${}^{A}_{Z}\mathbf{X}$ Element symbol

Atomic number

For further information, refer to page 102 in the textbook.

Question 1

What is meant by the following terms?

a mass number of a nucleus

b atomic number of a nucleus

Question 2

An atom of Beryllium isotope ${}^{9}_{4}\text{Be}$ has in its nucleus

A 4 protons only	**B** 4 neutrons only	**C** 4 protons and 4 neutrons
D 4 protons and 5 neutrons	**E** 5 protons and 4 neutrons	**F** 4 protons and 9 neutrons

Question 3

Determine the number of protons, neutrons and nucleons in these isotopes.

a $^{226}_{88}\text{Ra}$

b $^{35}_{17}\text{Cl}$

c $^{184}_{74}\text{Ta}$

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*Do questions **1-4** in chapter 7 of the textbook.*

ISOTOPES, RADIOISOTOPES and IONS

Isotopes

All atoms of a particular element will have the same number of protons but may have a different number of neutrons. For example, the nucleus of the hydrogen atom contains one proton, but some hydrogen nuclei contain a neutron in addition to the proton. And in rare instances, a hydrogen atom may contain two neutrons in addition to the proton. These are called **isotopes**. Isotopes have the same chemical properties but different physical properties.

The most common isotope of Hydrogen is $^{1}_{1}\text{H}$ The double mass hydrogen isotope $^{2}_{1}\text{H}$ is called *deuterium*. “Heavy water” is the name usually given to H_2O in which one or both of the H atoms have been replaced with deuterium atoms. Deuterium naturally occurs about 1 in 6000 Hydrogen atoms. The triple mass hydrogen isotope $^{3}_{1}\text{H}$, which is radioactive is called *tritium*, occurs naturally less than 1 in 10^{17} atoms.

All elements have a variety of isotopes. More than 2000 distinct isotopes, radioactive and stable, are known.

Radioisotopes

Most atoms are stable; however, some naturally occurring isotopes are unstable. An unstable nucleus may spontaneously lose energy by emitting a particle and change into a different element or isotope. Unstable atoms are radioactive and an individual radioactive isotope is known as a **radioisotope**. There are over 2000 known radioisotopes, most are artificially produced.

Ions

An **ion** is an atom with an overall charge. The charge can be positive or negative. Positive ions form when electrons are removed from a neutral atom and negative ions when electrons are added to a neutral atom.

The following information relates to Questions 4 and 5

Nuclide	Proton number	Neutron number	Electron number
V	19	20	19
W	20	22	20
X	20	22	18
Y	18	22	18
Z	18	20	18

Question 4

The letters representing isotopes of the same element are

A V & Z **B** W & X **C** W & X & Y **D** Y & Z

Question 5

The letter representing an ion is

A V **B** W **C** X **D** Y

Question 6

Which two of the following can be the isotope of $^{14}_{7}N$

A $^{15}_{7}N$ **B** $^{16}_{7}N$ **C** $^{14}_{8}N$ **D** $^{14}_{6}N$

Types of Nuclear Radiation

Alpha Radiation $^{4}_{2}\alpha$

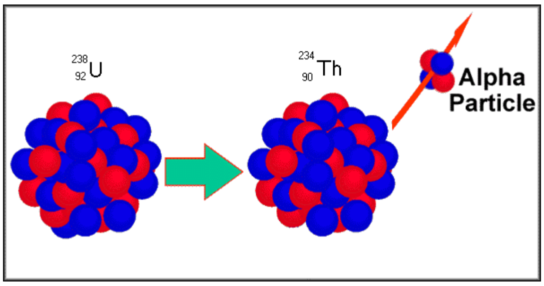
Alpha particle radiation consists of two neutrons and two protons, as they are charged they are affected by both electric and magnetic fields. The speed of the α-particle depends very much on the source, but typically are about 10% of the speed of light.
The capacity of the α -particle to penetrate materials is not very great, it usually penetrates no more than a few centimetres in air and is absorbed by a relatively small thickness of paper or human skin. However, because of their speed and size, they are capable of ionising a large number of atoms over a very short range of penetration.

This makes them relatively harmless for most sources that are about a metre or more away, as the radiation is easily absorbed by the air. Range in air at ordinary pressure is < 100mm, they are almost completely absorbed by a sheet of paper. But if the radiation sources are close to sensitive organs α -particle radiation is extremely dangerous.

When a nucleus emits an alpha particle, it loses two protons and two neutrons. Most alpha-emitters have high atomic numbers as the nucleus of these atoms are more unstable.

The symbols for an alpha particle are: $^{4}_{2}\alpha$, $^{4}_{2}\mathrm{He}^{2+}$ α or α^{2+}

When an atom changes into a different element, it is said to have undergone a *nuclear transmutation*. The new element formed is called the *daughter nucleus*. In any nuclear reaction, including radioactive decay, atomic and mass numbers are conserved.



$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha + \text{energy}$$

(<u>Investigation</u>: If you have access to an old watch that always glows in the dark. Take it into a completely dark room, wait for your eyes to adjust, and then examine the hands with a very strong magnifying glass. You should be able to see individual flashes, which together seem to be a steady source of light to the unaided eye. Each flash occurs when an alpha particle ejected by a radium nucleus strikes a molecule of zinc sulphide).

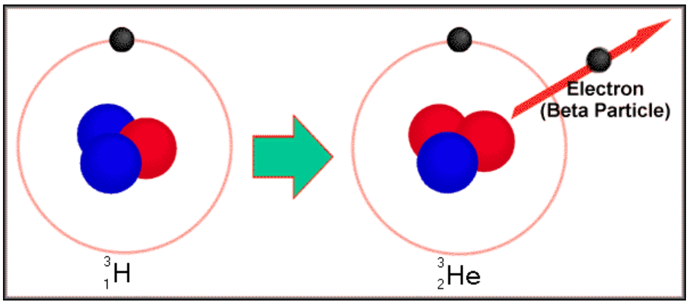
Beta Radiation $^{0}_{-1}\beta$

Beta-particle radiation consists of fast moving electrons or positrons (anti-electron, positively charged). Every β-particle carries either one negative or one positive electronic charge ($\pm 1.6 \times 10^{-19}$ coulomb: -e, +e). They are affected by electric and magnetic fields. The speed depends on the source, but it can be up to 90% of the speed of light.

β particles can penetrate up to 1 m of air. They are stopped by a few millimetres of aluminium or perspex. Their ionising capacity is much less than that of α-radiation, but they are very dangerous if ingested.

Beta particles emanate from the nucleus of radioactive nuclei that has too many neutrons for stability. A neutron spontaneously decays into a proton, an electron, and an uncharged, low-mass particle (approximately 10^{-5} the mass of an electron), called an antineutrino $\bar{\upsilon}$. The electron and antineutrino are emitted to restore the nucleus to a more stable state.

The force responsible for beta emissions is called the *weak interaction* or *weak force*



The nuclear decay equation is $^{3}_{1}H \rightarrow {}^{3}_{2}He + {}^{0}_{-1}\beta + \overline{\upsilon}$ + energy.

Both the atomic and mass numbers are conserved.

Gamma Radiation γ

Just as there are energy levels for the orbital electrons of an atom, there are energy levels within the nucleus. Whereas electrons making transitions to lower orbits emit photons of light, similar changes of energy states within the nucleus result in the emission of gamma rays (high energy photons, outside the visible spectrum). As gamma radiation is part of the electromagnetic spectrum it travels at the speed of light (3×10^8 m/s). Gamma radiation does not consist of charged particles; it is a form of very short wavelength electromagnetic energy.

Gamma radiation is very difficult to stop, it takes up to 30mm of lead. Although the ionising capacity of γ radiation is considerably smaller than that of beta-radiation, their high penetration power means that they are dangerous even at a distance. They can penetrate our bodies and hit sensitive organs. They are particularly dangerous if ingested or inhaled.

Gamma rays are electromagnetic waves, similar in nature to light waves and x-rays. They have no charge and do not alter the mass number of the nucleus that emits them.

A common example of a gamma ray emitter is iodine-131. Iodine-131 decays by beta and gamma emission to form xenon-131.

$$^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e + {}^{0}_{0}\gamma$$

Gamma ray decay alone occurs when a nucleus is left in an energised or excited state following an alpha or beta decay. This excited state is known as the *metastable state* and it usually only lasts a very short time. The equation above can be more strictly written as:

$$^{131}_{53}I \rightarrow {}^{131m}_{54}Xe + {}^{0}_{-1}e$$

$$^{131m}_{54}Xe \rightarrow {}^{131}_{54}Xe + {}^{0}_{0}\gamma$$

The 'm' denotes an unstable or metastable state. Cobalt-60 and technetium-99 also exist in metastable states.

Ionising radiation

Alpha particles, beta particles and gamma rays all originate from the nucleus of a radioisotope. A property of ionising radiation is its ability to ionise atoms. That is, this type of radiation can cause an electrically neutral atom to lose an electron, the atom becomes charged, and we call it an ion. In the cells of living animals, ionising radiation can create ions that are chemically reactive, which can lead to the damage or destruction of cells. Short term harmful effects are called **somatic** effects and long term hereditary effects are called **genetic**.

Type of radiation emitted & symbol	Nature of the radiation	Nuclear Symbol	**Penetrating power, and what will block it** (more dense material, more radiation absorbed BUT smaller mass or charge of particle, more penetrating)	**Ionising power –** the ability to remove electrons to form positive ions
α Alpha	a helium nucleus of 2 protons and 2 neutrons, mass = 4, charge = +2	${}^{4}_{2}\alpha$	Low penetration, biggest mas and charge, stopped by a few cm of air or thin sheet of paper	Very high ionising power, the biggest mass and charge of the three radiations, the biggest 'punch'.
β Beta	High kinetic energy electrons, mass = 1/1850, charge = -1	${}^{0}_{-1}\beta$ ${}^{0}_{-1}e$	Moderate penetration, 'middle' values of charge and mass, most stopped by a few mm of aluminium	Moderate ionising power, with a smaller mass and charge than the alpha particle.
γ Gamma	Very high frequency electromagnetic radiation, mass = 0, charge = 0	${}^{0}_{0}\gamma$	Very highly penetrating, smallest mass and charge, most stopped by a thick layer of steel or concrete, but even a few cm of lead doesn't stop all of it.	The lowest ionising power of the three, gamma radiation carries no electric charge and has no mass, so not much of a 'punch' when colliding with an atom.

For further information on the types of nuclear radiation, refer to pages 103-107 in the textbook.

Question 7

What are Alpha particles and where they come from?

Question 8

What are Beta particles and where they come from?

Question 9

What are gamma rays and where do they come from?

Question 10

Consider this list of different types of radiation: alpha particles, X-rays, infrared radiation, beta particles, microwaves, gamma rays. Which of these:

a) is a form of electromagnetic radiation?

b) has a positive electrical charge?

c) consists of four nucleons?

d) is a fast moving electron?

e) is able to ionise matter?

f) has the greatest penetrating ability?

(one or more answers)

Question 11

When an atom undergoes β-decay

A The mass number decreases by 4 and the atomic number decreases by 2
B The mass number decreases by 2 and the atomic number decreases by 4
C The mass number increases by 1 and the atomic number is constant
D The mass number is constant and the atomic number increases by 1

Question 12

When an atom undergoes α-decay

A The mass number decreases by 4 and the atomic number decreases by 2
B The mass number decreases by 2 and the atomic number decreases by 4
C The mass number increases by 1 and the atomic number is constant
D The mass number is constant and the atomic number increases by 1

Question 13

(Gamma) γ-rays are

A electromagnetic radiation
B negatively charged particles
C positively charged particles
D uncharged particles

Question 14

An alpha particle consists of

A 2 protons and 2 electrons
B 4 protons
C 2 protons and 2 neutrons
D 2 neutrons and 2 electrons

Question 15

Certain atoms emit gamma radiation because

A	they have a large nucleon number	**B**	their nuclei emit electrons
C	their nuclei contain protons and neutrons	**D**	their nuclei are unstable

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Question 16

The radiation which is the least powerful ioniser is?

A	gamma rays	**B**	neutrons
C	alpha particles	**D**	beta particles

Question 17

Which one of the following best describes the relative speeds at which alpha, beta, and gamma particles travel after being emitted from radioisotopes?

A Alpha is the slowest, beta and then gamma

B Beta is the slowest, gamma and then alpha

C Gamma is the slowest, alpha and then beta

D Gamma is the slowest, beta and then alpha

Question 18

Which radiation has no mass or charge?

A	gamma rays	**B**	neutrons
C	alpha particles	**D**	beta particles

For questions 19 and 20 use the answer key at right.

Question 19

A nucleus of a radioactive isotope emits a β^- particle.
What happens to

(i) its atomic number (ii) its mass number?

Question 20

Another radioactive nucleus emits an α particle.
What happens to

(i) its atomic number (ii) its mass number?

ANSWER KEY

A	It increase by 4
B	It increase by 2
C	It increases by 1
D	It remains the same
E	It decreases by 1
F	It decreases by 2
G	It decreases by 4

For questions 21 and 22 use the following information.

The radioactive nuclide $^{214}_{83}\text{Bi}$ can undergo either α or β decay.

These decays are

$$^{214}_{83}\text{Bi} \rightarrow \text{Q} + \alpha \qquad ^{214}_{83}\text{Bi} \rightarrow \text{R} + \beta^{-}$$

Question 21

Which of the following (**A – F**) below gives the correct **atomic numbers** for the isotopes Q and R?

	Q	R
A	83	82
B	81	84
C	81	83
D	81	82
E	79	84
F	79	82

Question 22

Which of the following (**A – F**) below gives the correct **mass numbers** for the isotopes Q and R?

	Q	R
A	214	214
B	210	215
C	210	214
D	210	213
E	208	215
F	208	214

MEASURING ENERGY

An **electron-volt** is an extremely small quantity of energy. It is equal to 1.6 × 10^{-19} J
MeV is a million electron-volts.

Property	**α particle**	**β-particle**	**γ ray**
Mass	heavy	Light	none
Charge	+2	-1	none
Typical energy	~ 5MeV	~ 1 Mev	~0.1 Mev
Range in air	100 mm	< 4 m	200 metres
Aluminium	0.2 mm	6 mm	500 mm
Lead	0.01 mm	0.4 mm	30 mm
Relative penetration power	1	100	10 000
Relative ionising power	10 000	100	1

Question 23

An electron-volt equals 1.6 × 10^{-19}J. How much energy in Joules does a 4.2 MeV alpha particle have?

A 1.6 × 10^{-19}J **B** 6.72 × 10^{-13}J

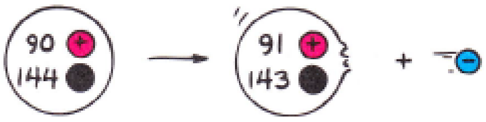
C 6.72 × 10^{-19}J **D** 3.81 × 10^{-26}J

TRANSMUTATIONS

When a nucleus emits and alpha or beta particle, a different element is formed. This changing of one chemical element to another is called **transmutation**. Consider uranium-238, the nucleus of which contains 92 protons and 146 neutrons. When an alpha particle is ejected, the nucleus is reduced by two protons and two neutrons. An element is defined by the number of protons in the nucleus, so the new element is thorium.

$$^{238}_{92}\text{U} \rightarrow ^{234}_{90}\text{Th} + ^{4}_{2}\text{He}$$

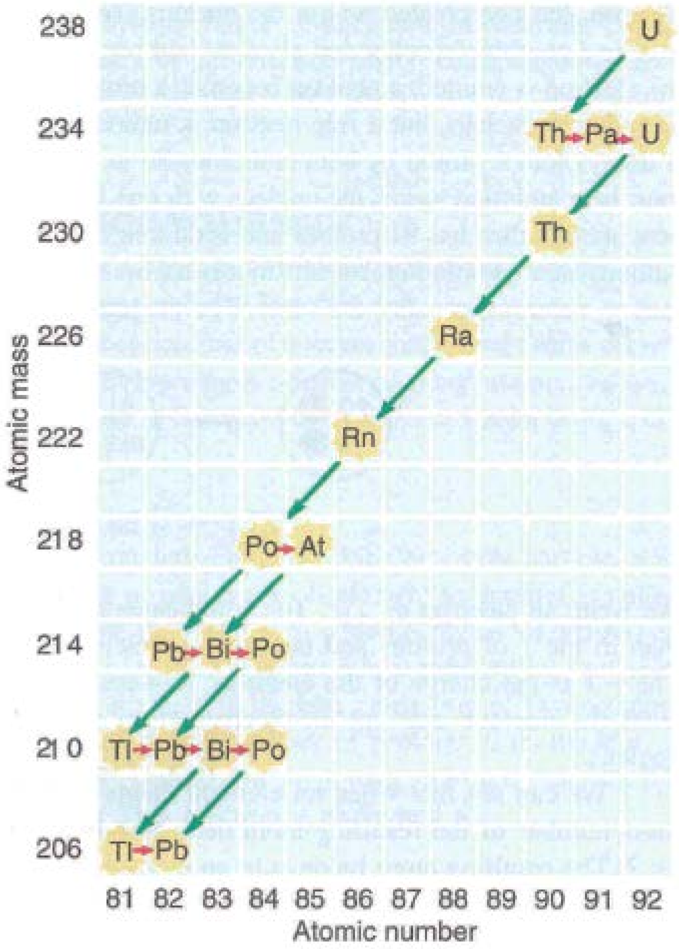
In equations such as this, the mass numbers and the atomic numbers balance.



$$^{234}_{90}\text{Th} \rightarrow ^{234}_{91}\text{Pa} + ^{0}_{-1}e$$

Thorium-234, the product of this reaction, is also radioactive. When it decays, it emits a beta particle. (beta particle is an electron-not an orbital electron, but one created within the nucleus. When the electron is emitted, a neutron becomes a proton. The new nucleus now has 91 protons, so it is *protactinium*.

Gamma emission results in no change in either the mass number or the atomic number.



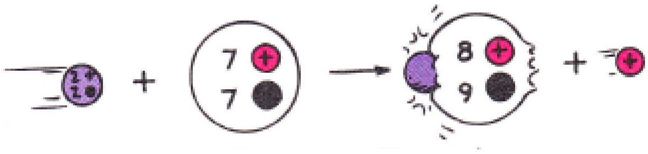
Artificial transmutation

Artificial radioisotopes are manufactured by bombarding stable nuclei with neutrons. This process is known as **artificial transmutation**.

The nuclear transformation is: ${}^{1}_{0}n + {}^{59}_{27}Co \rightarrow {}^{60}_{27}Co$.

The artificial radioisotope cobalt-60 (half-life 5.27 years) is used extensively in the treatment of cancer. It decays by emitting a beta particle.

Rutherford (1919) was the first to succeed in transmuting a chemical element. He bombarded nitrogen nuclei with alpha particles and succeeded in transmuting nitrogen into oxygen:



Nuclide	Historic name (short)	Historic name (long)	Decay mode	Half-life	MeV	Decay product
^{238}U	U	Uranium	α	$4.468 \cdot 10^9$ a	4.270	^{234}Th
^{234}Th	UX_1	Uranium X1	β^-	24.10 d	0.273	^{234m}Pa
^{234m}Pa	UX_2	Uranium X2	β^- 99.84 % IT 0.16 %	1.16 min	2.271 0.074	^{234}U ^{234}Pa
^{234}Pa	UZ	Uranium Z	β^-	6.70 h	2.197	^{234}U
^{234}U	U_{II}	Uranium two	α	245500 a	4.859	^{230}Th
^{230}Th	Io	Ionium	α	75380 a	4.770	^{226}Ra
^{226}Ra	Ra	Radium	α	1602 a	4.871	^{222}Rn
^{222}Rn	Rn	Radon	α	3.8235 d	5.590	^{218}Po
^{218}Po	RaA	Radium A	α 99.98 % β^- 0.02 %	3.10 min	6.115 0.265	^{214}Pb ^{218}At
^{218}At			α 99.90 % β^- 0.10 %	1.5 s	6.874 2.883	^{214}Bi ^{218}Rn
^{218}Rn			α	35 ms	7.263	^{214}Po
^{214}Pb	RaB	Radium B	β^-	26.8 min	1.024	^{214}Bi
^{214}Bi	RaC	Radium C	β^- 99.98 % α 0.02 %	19.9 min	3.272 5.617	^{214}Po ^{210}Tl
^{214}Po	RaC'	Radium C'	α	0.1643 ms	7.883	^{210}Pb
^{210}Tl	RaC"	Radium C"	β^-	1.30 min	5.484	^{210}Pb
^{210}Pb	RaD	Radium D	β^-	22.3 a	0.064	^{210}Bi
^{210}Bi	RaE	Radium E	β^- 99.99987% α 0.00013%	5.013 d	1.426 5.982	^{210}Po ^{206}Tl
^{210}Po	RaF	Radium F	α	138.376 d	5.407	^{206}Pb
^{206}Tl			β^-	4.199 min	1.533	^{206}Pb
^{206}Pb			–	stable	–	–

For further information, refer to pages 108-110 in the textbook.

Question 24

In the following reaction

$^{212}_{84}\mathrm{Po} \rightarrow \mathrm{X} + \text{an } \alpha \text{ particle,}$

The nuclide X is

A $^{212}_{80}\mathrm{Hg}$

B $^{210}_{80}\mathrm{Hg}$

C $^{210}_{82}\mathrm{Pb}$

D $^{208}_{82}\mathrm{Pb}$

E $^{212}_{82}\mathrm{Pb}$

In the chain of decays that lead from $^{214}_{83}\mathrm{Bi}$ to a stable nucleus $^{Z}_{A}\mathrm{X}$ one α particle, one β^- particle and 2 γ rays are emitted.

Question 25

What are the values of Z and A for nucleus X?

Via a decay chain a $^{237}_{93}\mathrm{Np}$ nucleus decays to $^{213}_{83}\mathrm{Bi}$ by emitting a number of α and β (e^-) particles.

Question 26

How many α particles are emitted in this decay chain?

Question 27

How many β (e^-) particles are emitted in this decay chain?

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*Do questions **5-16** in chapter 7 of the textbook.*

Effects on Humans

Exposure to radiation is impossible to avoid and our bodies are unable to sense how much radiation we are absorbing. A dose of γ radiation large enough to be lethal to a human being would only raise our temperature by one thousandth of a degree. The presence of background radiation, to which we are constantly exposed, is not a significant health risk.

To measure the amount of radiation, from a source, that is hitting a target, we need to know, the source, the half-life; the activity to calculate how much energy is being released. We also need to know how much of this is hitting the target to calculate how much is absorbed.

Absorbed dose

The absorbed dose is the radiation energy that has been absorbed per kilogram of target material.

$$\text{Absorbed dose} = \frac{\text{energy absorbed by tissue}}{\text{mass of tissue}}$$

Absorbed dose is measured in joules/kilogram or grays (Gy). 1 J/kg = 1 Gy

Dose equivalent

The different types of radiation are given weightings to reflect their biological impact.

Radiation	Quality factor
Alpha particles	20
Neutrons (>10keV)	10
Beta particles	1
Gamma rays	1
X-rays	1

The dose equivalent measured in sieverts (Sv) is given by:

Dose equivalent (Sv) = absorbed dose (Gy) × quality factor.

It is slightly more complicated than this because different parts of the body are much more vulnerable. Organs in which cell division occur, such as bone marrow, lungs, ovaries or testes are much more vulnerable. In Australia the average annual background radiation is around 2.0 mSv, or 2000 μSv.

The effects of radiation on humans

The somatic effects are the short-term effects, and the long-term effects are the genetic effects.

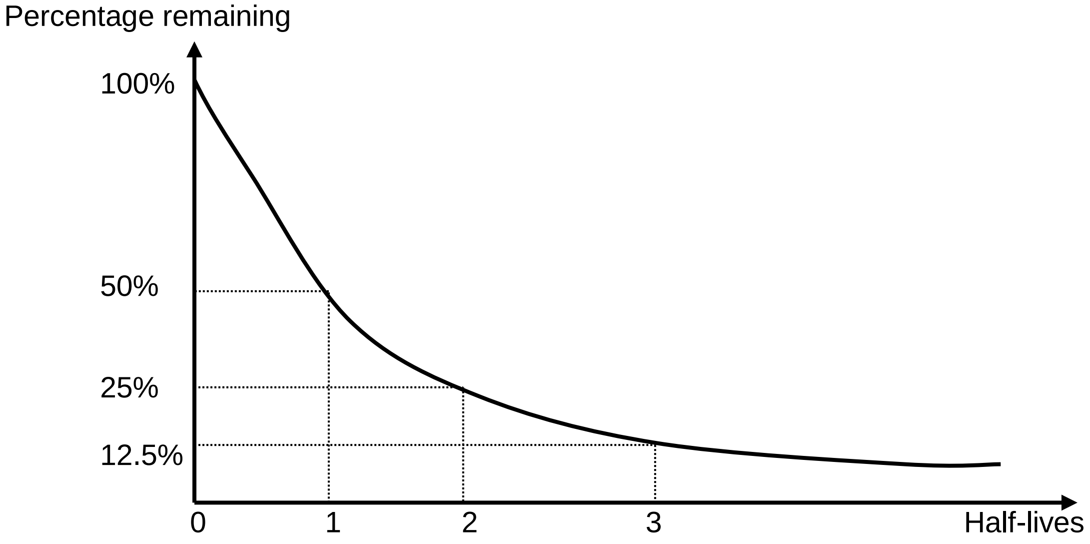
Whole body dose (Sv)	Symptom
<1	Non-fatal. Only minor symptoms such as nausea White blood cell level drops
2	Death unlikely. Radiation sickness, i.e nausea, vomiting and diarrhoea. Skin rashes. Hair loss. Bone marrow damaged
4	50% likelihood of death within 2 months. Severe radiation sickness. High probability of leukaemia and tumours
8	Almost certain death within 1 or 2 weeks due to damage of the gastro intestine. Acute radiation sickness - convulsions, lethargy

The genetic effects of radiation are

- Chromosome aberrations involving changes in the actual number or structure of the chromosomes
- Genetic mutations which can lead to deformation in future generations

Half-life of a radioisotope

A radioactive substance is one whose nuclei are unstable. At random instants the nuclei disintegrate with the emission of particles or rays or both. The average time taken for one-half of a given number of atoms to disintegrate is known as the half-life period ($T_{\frac{1}{2}}$) of that substance. After a further period T one half of the remaining nuclei will disintegrate, and so on. The rate of disintegration varies widely; half-lives vary from a fraction of a second to 10^{10} years. In the case of the heavy radioactive elements radioactivity progressively leads to the formation of a series of other elements, each with its own half-life until a final stable element is reached that is not radioactive.



The decay process is random, these are average results, and it is impossible to predict what will happen to any individual nucleus. The decay is as exponential relationship.
Every isotope of every radioactive element has its own characteristic half-life. Uranium-238, for example, has a half-life of 4.5 billion years, while the shortest half-lives of elementary particles are on the order of 10^{-23} second, the time light would take to travel across the nucleus.

Isotope	Emission	Half-life	Application
Natural			
Polonium-214	α	0.00016 seconds	Nothing at this time
Carbon-14	β	5730 years	Carbon dating of fossils
Uranium-235	α	700 000 years	Nuclear fuel, rock dating
Uranium-238	α	4 500 million years	Nuclear fuel, rock dating
Artificial			
Technetium-99m	β	6 hours	Medical tracer
Sodium-24	β	15 hours	Medical tracer
Iodine-131	β	8 days	Medical tracer
Phosphorus-32	γ	14.3 days	Medical tracer
Cobalt-60	β	5.3 years	Radiation therapy
Americium-241	α	460 years	Smoke detectors
Plutonium-239	α	24 000 years	Nuclear fuel, rock dating

For further information, refer to page 107 in the textbook.

Activity
The strength of any given radioactive source is determined by its activity. The activity of the sample indicates the number of radioactive decays that are occurring in the sample each second. Activity is measured in Becquerels (Bq), where 1 Bq = 1 disintegration per second. The activity of any radioactive sample will decrease with time. Over a half-life, the activity of a sample will halve.

Question 28

A particular nucleus in a sample of radioactive material is known to have survived for 5 half-lives. The probability that *this nucleus* will decay during the next half-life is:

A. $\frac{1}{6}$ **B.** $\frac{1}{5}$ **C.** $\frac{1}{2}$ **D.** 1 **E.** $\frac{1}{32}$

F. $\frac{31}{32}$ **G.** $\frac{5}{6}$ **H.** 2

For questions 29 and 30 use the following information.

The decay constant of a radioactive isotope is defined as the fraction of undecayed atoms that undergo radioactive decay in unit time. A particular isotope which has a half-life of 10 days has a decay constant of 0.07 per day.

Question 29

A sample of 1.0 x 10^{-3} gm of the isotope is prepared. What mass of the isotope remains after 20 days?

Question 30

What is the decay constant (in day^{-1}) after 20 days?

Question 31

The half-life of $^{99}_{43}\text{Tc}$ is 6.0 hr. The time taken for a specimen of $^{99}_{43}\text{Tc}$ to be removed from a nuclear reactor and delivered for use at a hospital is 18 hr.

What mass of $^{99}_{43}\text{Tc}$ must be removed from the reactor for 1μg to be delivered to the hospital?

Radon has a half-life of 3.8 days. In an experiment, a student starts with a sample containing 16 mg of radon.

Question 32

After what time interval has the amount of radon decreased to 2.0 mg?

The radioisotope ${}^{60}_{24}\mathrm{Co}$ has a half-life of 5.0 years. Gamma radiation from a ${}^{60}_{24}\mathrm{Co}$ source is used to treat cancer. Hospitals using such sources for therapy usually replace the source when its activity has fallen to 25% of its original value.

Question 33

After how many years must the source be replaced?

A radioactive form of the element technetium, ${}^{99}\mathrm{Tc}$, is often used in medical diagnosis. A sample of this isotope is delivered to a hospital at 9:00 am on a Monday morning. At 9:00 am the following morning, its activity is found to have fallen to $\frac{1}{16}$ of its value on delivery.

Question 34

What is the half-life, in hours, of this isotope?

One of the most common radioactive isotopes used in medicine in Australia is technetium 99m, ^{99m}Tc, where ‘m’ indicates an excited state of technetium.
Technetium 99m is prepared by neutron bombardment of molybdenum 98 in a nuclear reactor. The molybdenum absorbs a neutron, and then beta decays to technetium 99m.

Question 35

Which of the following equations correctly describes this process?

A $^{98}_{42}\text{Mo} + ^{1}_{0}\text{n} \rightarrow ^{98}_{42}\text{Mo} \rightarrow ^{99m}_{43}\text{Tc} + \beta^{-} + \gamma$

B $^{98}_{42}\text{Mo} + ^{1}_{0}\text{n} \rightarrow ^{99}_{42}\text{Mo} \rightarrow ^{99m}_{42}\text{Tc} + \beta^{-} + \gamma$

C $^{98}_{42}\text{Mo} + ^{1}_{0}\text{n} \rightarrow ^{99}_{42}\text{Mo} \rightarrow ^{99m}_{43}\text{Tc} + \beta^{-} + \gamma$

D $^{98}_{42}\text{Mo} + ^{1}_{0}\text{n} \rightarrow ^{98}_{42}\text{Mo} \rightarrow ^{99m}_{42}\text{Tc} + \beta^{-} + \gamma$

For questions 38 and 39 use the following information.

$^{56}_{25}\text{Mn}$ is a nucleus which decays to a nucleus *D* by beta (β^-) decay.

Question 36

How many neutrons (*N*) and protons (*Z*) does the nucleus *D* have?

$^{56}_{25}\text{Mn}$ which has a half-life of 2½ hours is made from the stable isotope ^{55}Mn by irradiating it with neutrons. At the end of a particular irradiation the ratio of ^{56}Mn to ^{55}Mn nuclei is 1.0 x 10^{-10}.

Question 37

Ten hours after the irradiation is completed, what is the value of the following quantity?

$$\frac{\text{number of nuclei } ^{56}\text{Mn}}{\text{number of nuclei } ^{55}\text{Mn}}$$

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*Do questions **17-23** in chapter 7 of the textbook.*

Carbon dating

While a plant or animal is alive, it is exchanging carbon with its surroundings, so that the carbon it contains will have the same proportion of ^{14}C as the biosphere. Once it dies, it ceases to acquire ^{14}C, but the ^{14}C that it contains will continue to decay, and so the proportion of radiocarbon in its remains will gradually reduce. Because ^{14}C decays at a known rate, the proportion of radiocarbon can be used to determine how long it has been since a given sample stopped exchanging carbon—the older the sample, the less ^{14}C will be left.

To calculate how old a material is the following formula can be used: $N = N_0 e^{(t/\tau)}$

Where N_0 is the number of atoms of the isotope in the original sample, N is the number of atoms left at time t, and τ is the mean life for the particular isotope.

The equation can be rearranged to the more convenient format of $t = \tau \ln(N_0 / N)$

The mean life is the average amount of time that an element remains in its unstable state. It is also the amount of time it takes for the activity of a given sample to disintegrate to 1/e of the initial activity (this is the same as a half-life except instead of disintegrating to 1/2 it disintegrates to 1/e). The mean life and the half-life ($T_{1/2}$) are related by $T_{1/2} = \tau \ln(2)$,

therefore the mean life of carbon-14 is $\tau = \frac{5730}{\ln(2)}$ =8267 years.

For questions 38 and 39 use the following information.

The $^{12}_{6}C$ isotope of carbon is stable but $^{14}_{6}C$ is unstable, decaying by β^- emission with a half-life of 5740 years.

Question 38

When $^{14}_{6}C$ decays it forms

A. $^{13}_{6}C$ **B.** $^{14}_{5}B$ **C.** $^{14}_{7}N$

D. $^{13}_{5}B$ **E.** $^{13}_{7}N$ **F.** $^{15}_{6}C$

In the atmosphere and in living matter, the relative abundance of $^{12}_{6}C$ and $^{14}_{6}C$ is constant; but in dead organic matter, decay of $^{14}_{6}C$ alters the ratio.

Question 39

Two samples of organic matter were found at one archaeological digging. At one site the ratio of $^{12}_{6}C$ to $^{14}_{6}C$ was greater than at the other by a factor of 8. By how many years does one sample pre-date the other?

For questions 40 and 41 use the following information.

Uranium-238 (^{238}U) decays through a chain on nuclei, leading eventually to lead-206 (^{206}Pb) The effective half-life for the whole process is about 4.5 x 10^9 years. Some of the oldest uranium-bearing rocks on Earth contain roughly equal numbers of atoms of ^{238}U and ^{206}Pb.

Question 40

If we assume that all of the ^{206}Pb has come from the decay of ^{238}U, approximately how old are these rocks?

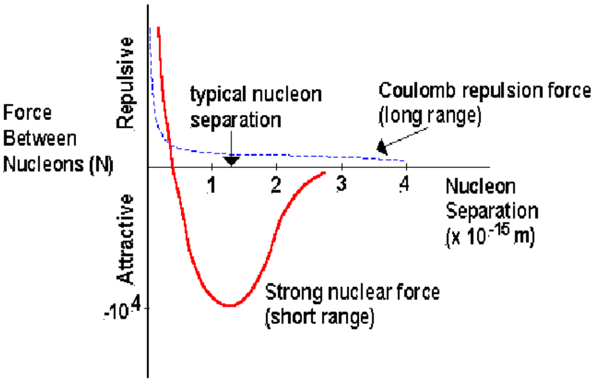
Question 41

What is the total number of alpha particles emitted in the decay of a ^{238}U nucleus to ^{206}Pb?

WHY ATOMS ARE RADIOACTIVE

The positively charged and closely spaced protons in a nucleus have huge electrical forces of repulsion between them. Why don't they fly apart because of this huge repulsive force?

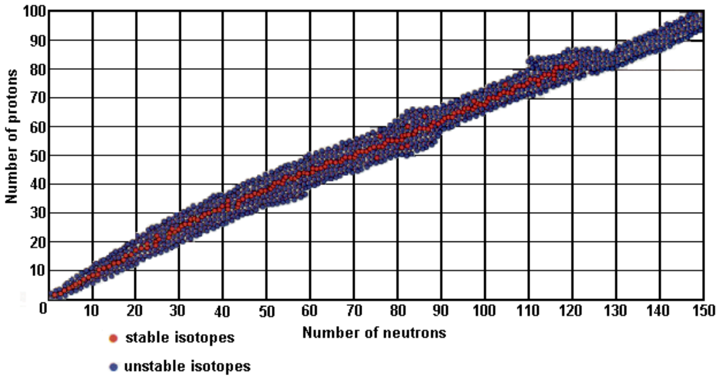
Because there is an even larger force within the nucleus – the nuclear force. Both neutrons and protons are bound to each other by this attractive force. The principle part of the nuclear force, the part that holds the nucleus together, is called the *strong interaction*, *strong nuclear for*ce (or just *strong force*). This force acts only over a very short distance, ~ 10^{-15} m, and is close to zero at greater separations. The strong force is both attractive and repulsive depending on the distance, as seen from the graph. Electrical interaction, on the other hand, weakens as the inverse square of separation distance and is a relatively long range force. So as long as the protons are close together, as in small nuclei, the nuclear force easily overcomes the electrical force of repulsion. But for distant protons, like those on opposite edges of a large nucleus, the attractive nuclear force may be small in comparison to the repulsive electrical force. Hence the larger a nucleus the more unstable it is.



The presence of the neutrons also plays a large role in nuclear stability. In general terms extra neutrons increase stability. If the uranium nucleus were to have equal numbers of protons and neutrons, 92 neutrons and 92 protons, it would fly apart due to the electrical repulsion. Even so, the U-238 ($^{238}_{92}U$) nucleus is still unstable because of the electrical forces.

There is an electrical repulsion between *every pair* of protons in the nucleus, but there is not a substantial nuclear attractive force between every pair of protons in the nucleus (due to separation distance).

All nuclei having more than 82 protons are unstable. In this unstable environment, alpha and beta emissions take place. The force responsible for beta emissions is called the *weak interaction*. It acts on leptons as well as nucleons. When an electron is created in beta decay, another lighter particle called an *antineutrino* is also created and shoots out of the nucleus.



When an unstable nucleus undergoes radioactive decay, it may eject a particle. The two particles are alpha and beta particles, gamma radiation may also be emitted, but this is not a particle. The three decay processes all come from the nucleus; the electron cloud does not give of nuclear radiation.

For further information, refer to page 112 in the textbook.

BINDING ENERGY

As technology improved, and more precise measurements could be made. Scientists noticed that the mass of a nucleus was always less than the mass of its constituent parts (the protons and neutrons). For example;

The mass of an alpha particle is 4.00153 u

Whereas the mass of the constituent parts is

Protons	2×1.00728 u
Neutrons	2×1.00866 u
Total	4.03188 u

Where u is the unified atomic mass unit, also known as Dalton (Da).
u = 1.66054×10^{-27} kg = 931.494 MeV/c^2. u is approximately the mass of one nucleon, numerically equivalent to 1 g/mol, and is defined as one twelfth of the mass of an unbound, neutral carbon-12 atom.

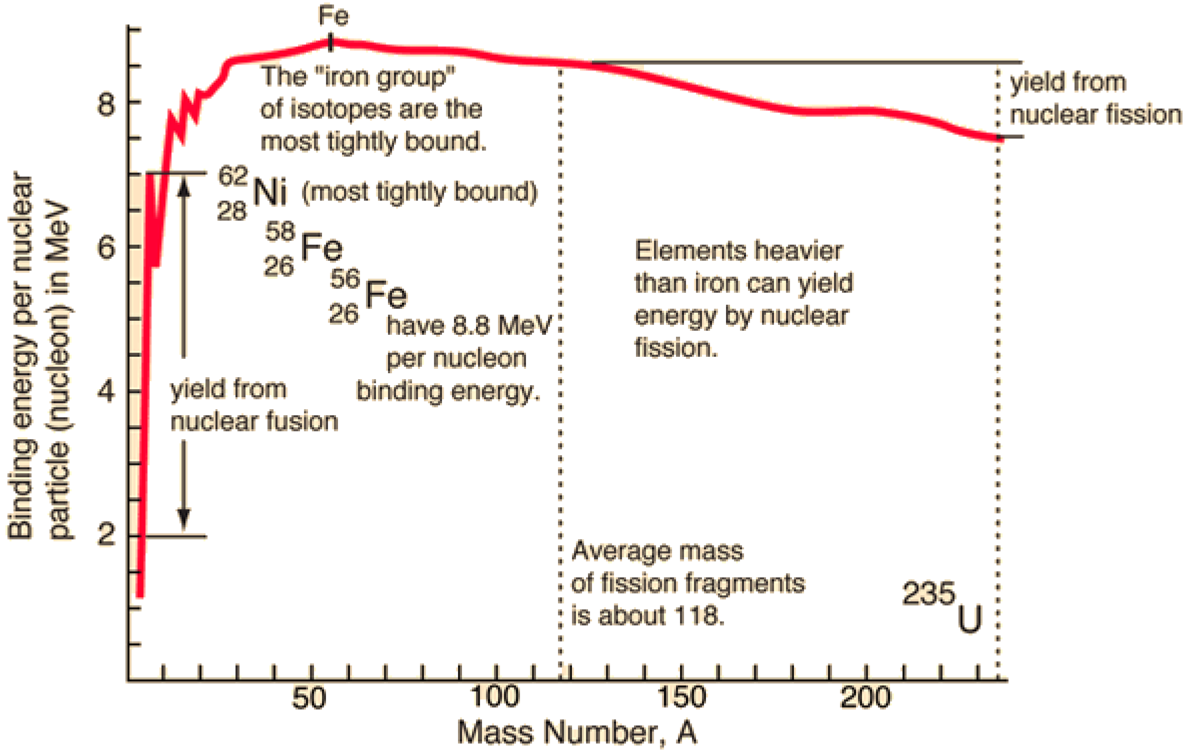
This difference in mass is a measure of the strength of the strong nuclear force that holds the nucleus together, this is known as the nuclear binding energy. The binding energy is different for each element, and each of their isotopes. The graph below shows the binding energy per nucleon for different mass numbers.

The binding energy can be calculated using Einstein's relationship

$$E=mc^2$$

Where E is the nuclear binding energy, m is the mass difference, and c is the speed of light.

Elements or isotopes with a high binding energy are more stable.



SPLITTING THE ATOM - NUCLEAR FISSION

In 1932 James Chadwick discovered the neutron, up until then scientists had been trying to split the atom by firing alpha particles at the nucleus. This did not work because the charged alpha particles were repelled by the nucleus. The uncharged neutrons changed this. In 1934 Enrico Fermi bombarded uranium nuclei with neutrons, the nuclei absorbed the neutrons and split in two. This is called **nuclear fission.**

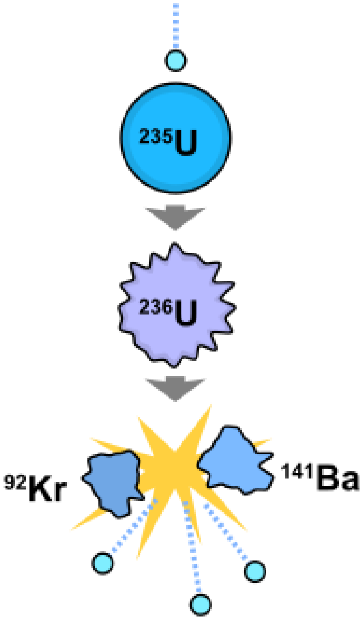
Because the resulting fragments are not the same element as the original atom, fission is a form of nuclear transmutation. While alpha and beta decay also change the element this is not generally thought of as fission, as the speeds and masses of the resulting fragments are not comparable.

Nuclear fission is when an atomic nucleus splits into two or more pieces, this process is often triggered by the absorption of a neutron. Nuclides that are capable of undergoing nuclear fission are called fissile. It is basically only uranium-235 and plutonium-239 are readily fissile. Uranium-238 and thorium-232 are slightly fissile.

When the nucleus splits it also releases more neutrons and a large amount of energy.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{91}_{36}Kr + {}^{142}_{56}Ba + 3\,{}^{1}_{0}n + \text{energy} $$

Krypton-91 and barium-142 are known as the fission fragments. A uranium-235 nucleus can split in many different ways, up to 40 different pairs of fission products are possible most are beta emitters. These fission fragments make up the bulk of the high-level waste produced by nuclear reactors. On average uranium-235 produces ~ 2.5 neutrons per fission and plutonium-239, ~ 2.9 neutrons per fission. These neutrons can go on to trigger more fission reactions.



An enormous amount of energy is released during each fission reaction. In any fission reaction, the combined mass of the incident neutron and the target nucleus is always greater than the combined mass of the fission fragments and the released neutrons. This change in mass (only about 0.1% of the total mass) is what is converted into energy, using $E=mc^2$.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n + 160\text{MeV} $$

$$ 160 \text{ MeV} = 2.6 \times 10^{-11} \text{ J.} $$

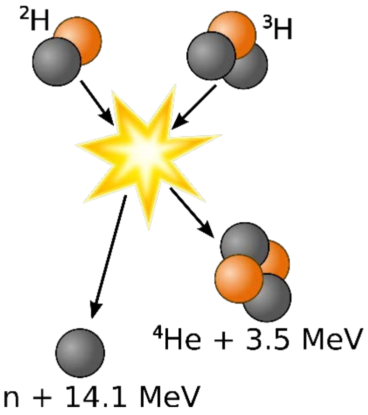
One kilogram of uranium-235 contains ~2.6×10^{24} nuclei. This means that the total energy available per kilogram = $2.6 \times 10^{24} \times 2.6 \times 10^{-11} = 6.8 \times 10^{13}$ J. It would require the combustion of 3×10^{6} kg of coal to release the same amount of energy.

Combining Atoms – Nuclear Fusion

Nuclear fusion is the reverse process to fission. It is the process of fusing two atoms together and creating a larger atom. Massive amounts of energy are either being consumed or released during this process.

Nuclear fusion is the source of energy for stars. This is also how all the elements (up to iron for large stars) were made. During extreme events such as when a large star implodes, heavier elements can be created via fusion even though these transformations are not energetically favourable.

Nuclear Fusion is a nuclear reaction that requires massive amounts of energy to initiate, and massive amounts of energy to maintain as atoms repel each-other unless greatly heated. Nuclear fusion on earth, is a very hard reaction to perform, as it is only maintainable for a matter of seconds on earth, as the energy needed to create the nuclear reaction is very high, and is burned out at the beginning of the reaction. It is estimated that to perform a successful you would require a heat that would not be containable in any material. And so, as a result, scientists must create environments with massive amounts of pressure and heat in order for the reaction to occur successfully. As a result, nuclear fusion does not have many uses on earth, at least not yet...



For further information, refer to pages 113-118 in the textbook.

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*Do questions **24-34** in chapter 7 of the textbook.*