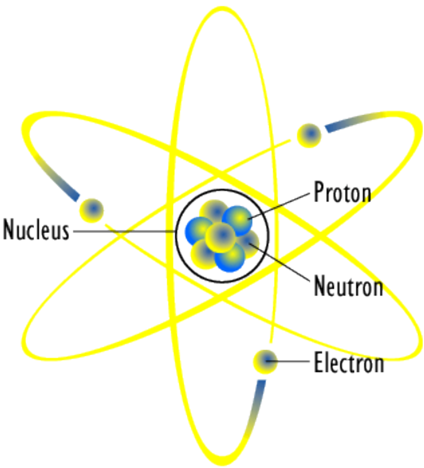
Croydon Maroondah College

Physics Unit 1

	Topic	Heinemann (H) and Jacaranda (J)[1]		
		Section	Pages	Questions
1.	**Atoms, Isotopes & Radioisotopes**	**Atomic structure**	**H123 J 23**	**1-5,9 1 – 5**

Part 1: ATOMS, ISOTOPES and RADIOISOTOPES

As you have been taught in previous years, the atom can be modelled as a planetary system, with the electrons orbiting the nucleus just planets orbit a star. In the diagram to the right you can see a representation of this, with 3 orbiting electrons around a nucleus consisting of 3 protons and 4 neutrons. ($^{7}_{3}Li$).



Rutherford is considered responsible for the development of our current understanding of the structure of matter. His model predicted that an atom consists of a positively charged nucleus surrounded by negatively charged electrons which move about the nucleus in definite energy states.[2]

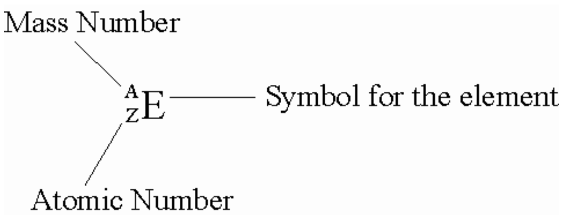
The nucleus is not a single body, but is made up of at least two kinds of particles, protons and neutrons, held together by a strong nuclear force[3]. The nucleus of an atom occupies 10^{-12} of the volume of the atom, yet it contains over 99% of its mass. Atoms are mostly empty space.

<u>Atomic number and mass number</u>

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.

<u>Shorthand for an atom</u>

The **atomic number** is the number of protons in the nucleus of an atom. This is equal to the number of electrons if the atom is neutral. The **mass number** is the total number of protons and neutrons in the nucleus. Protons and neutrons are sometimes called nucleons.



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[1] Jacaranda Questions are available in the online supplement. Jacaranda Questions are additional practice questions; only the questions from Heinemann are compulsory.

[2] See the Geiger-Marsden Gold Foil experiment: http://en.wikipedia.org/wiki/Rutherford_model

[3] More information on Strong Nuclear Force: http://theory.uwinnipeg.ca/mod_tech/node178.html

Isotopes
All atoms of a particular element will have the same number of protons but may have a different number of neutrons. These are called **isotopes**. Isotopes have the same chemical properties but different physical properties.

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. This process is called transmutation, and can occur naturally or be forced to occur artificially. Unstable atoms are radioactive and an individual radioactive isotope is known as a **radioisotope**. There are over 2000 known radioisotopes, but most are artificially produced.

Questions

Name an element with more than 4 isotopes and list them.

Hydrogen has three isotopes. What are their names and atomic masses?

What is heavy water?

	Topic	Heinemann (H) and Jacaranda (J)		
		Section	**Pages**	**Questions**
2.	**Alpha, Beta & Gamma Radiation**	**Decay types**	**H123**	**Q 10**
			H130	**Q1,2,4-10**
			J23	**Q8 - 10**
		Radiation properties	**H135**	**Q2-10**
			J23	**Q 6 -7, 16, 20**

Part 2: ALPHA, BETA and GAMMA RADIATION

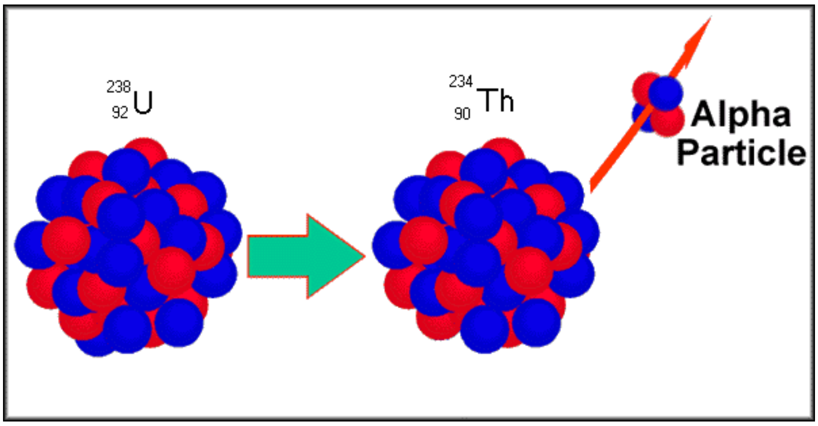
When an unstable nucleus undergoes radioactive decay, it may eject a particle. The two particles are alpha (α) and beta (β) particles, gamma (γ) radiation may also be emitted, but this is not a particle. The three decay processes all come from the nucleus; the electron cloud does not give of radiation.

Alpha decay ($^{4}_{2}\alpha$)

These are physically identical to helium nuclei, and so consist of two protons and two neutrons. When a nucleus emits an alpha particle, it loses two protons and two neutrons. Alpha particles are ejected with high speeds and are relatively easily absorbed by matter. Range in air at ordinary pressure is < 100 mm; they are almost completely absorbed by a sheet of paper. Most alpha-emitters have high atomic numbers.

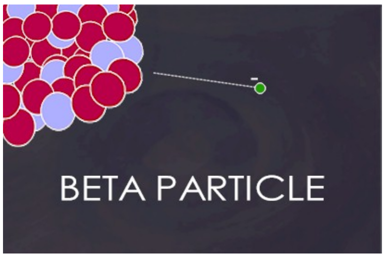
The symbol for an alpha particle can be: $^{4}_{2}\alpha$, $^{4}_{2}He^{2+}$ or α^{2+}

When an atom changes into a different element, it is said to have undergone a *nuclear transmutation*. The new element(s) formed is called the *daughter nucleus (nuclei)*. In any nuclear reaction, including radioactive decay, atomic and mass numbers are conserved. This means that the total number of nucleons is the same before and after the reaction.



$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}\alpha + energy(\gamma)$$

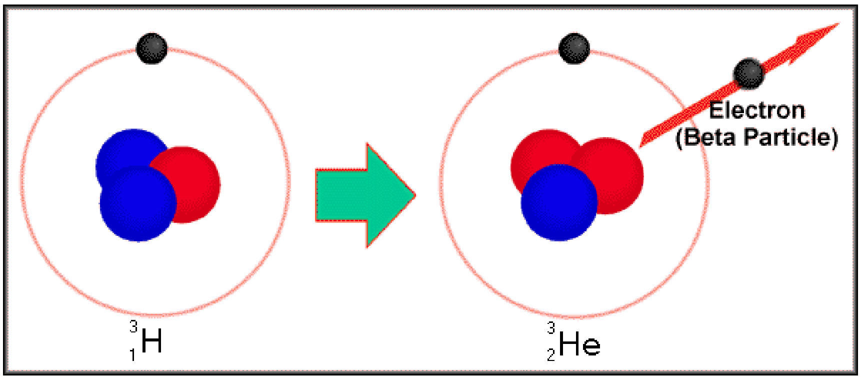
Beta decay ($^{0}_{-1}\beta$)



Beta particles are electrons; they carry away a negative charge equal in magnitude but opposite in polarity (if β^-. β^+ has the same polarity, but is rarer) to the charge of a proton ($q_\beta \cong -1.6\times10^{-19}$ C).
They emanate from the nucleus of radioactive nuclei that has too many neutrons for stability. A neutron spontaneously decays into a proton and an electron, and the electron (and an uncharged, mass less particle, called an antineutrino $\bar{\upsilon}$) are emitted to restore the nucleus to a more stable state. After beta decay, the mass number remains the same, but the atomic number increases by one.

The isotopes of carbon are $^{12}_{6}C$, $^{13}_{6}C$, $^{14}_{6}C$. Carbon-12 and carbon-13 are both stable but carbon-14 has too many extra neutrons, as so is unstable.

Here is another example of an unstable radioisotope, Hydrogen 3 (otherwise known as tritium). Tritium undergoes beta decay, converting one neutron to a proton and a β particle. This β particle is ejected from the nucleus, and the product of the reaction, Helium 3, is more stable.



The nuclear decay equation is

$$^{3}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{-1}\beta + \bar{\upsilon} + \text{energy}.$$

Both the atomic and mass numbers are conserved. On the left hand side, the mass number (A) is 3 and the atomic number (Z) is 1. On the right hand side, the mass number total of all products is 3 + 0 = 3. The atomic number total of the products is 2 + -1 = 1.

Gamma decay $^{0}_{0}\gamma$

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.

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

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:

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

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

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

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 is used extensively in the treatment of cancer. It decays by emitting a beta particle. Artificial transmutation can also be used to create different elements. (See page 8)

What is a neutrino and what role does it play in beta decay?

Name an element which is artificially created by transmutation

Alchemists are famous for trying to turn lead into gold (using a mythical ingredient called "The Philosopher's Stone".) They never succeeded. Explain why.

Properties of α, β, γ radiation.

Alpha particles, beta particles and gamma rays all originate from the nucleus of a radioisotope. A particle 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 (usually Hydroxide (OH^-) ions) that are chemically reactive, which can lead to the damage or destruction of cells or DNA. Short term harmful effects are called **acute** effects and long term hereditary effects are called **chronic**.

Alpha particles

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. But if the radiation sources are close to sensitive organs α-particle radiation is extremely dangerous.

Beta particles

Beta-particle radiation consists of fast moving electrons. 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. They are very dangerous if ingested.

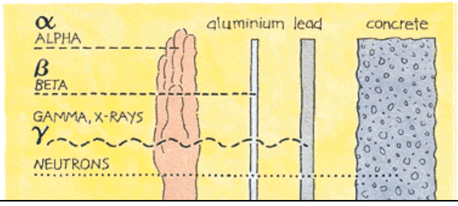
Gamma rays

Gamma radiation does not consist of charged particles; it is a form of very short wavelength electromagnetic energy, and part of the electromagnetic spectrum. They travel at the speed of light (3×10^8 m/s). 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 you inhale or ingested atoms that are emitting gamma rays.

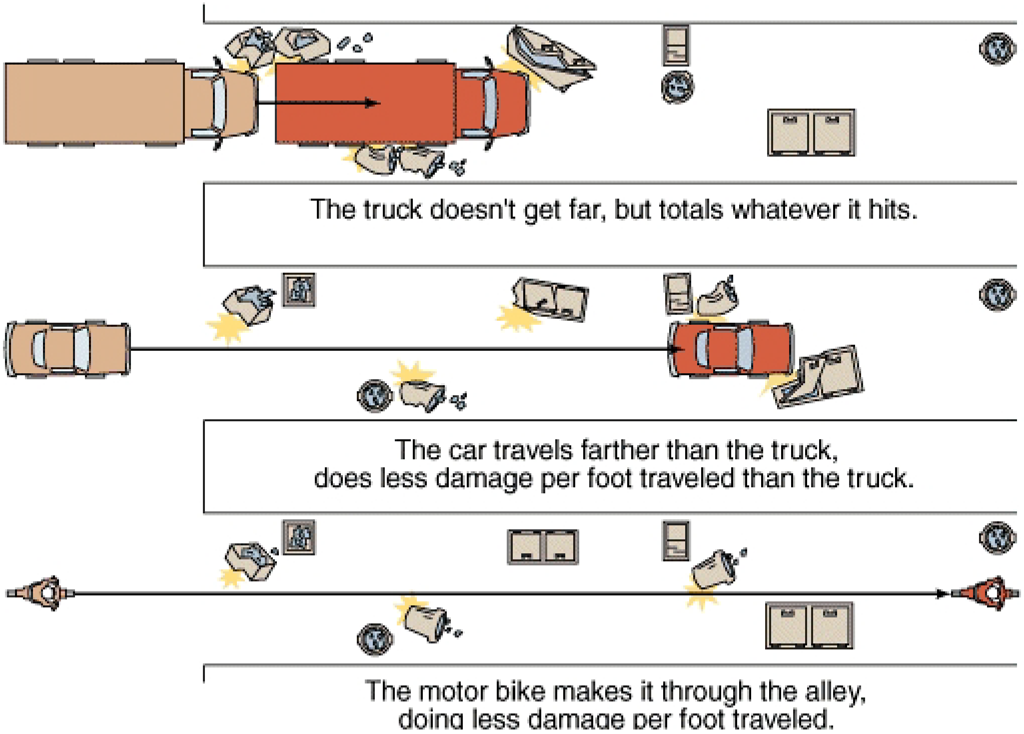
Measuring energy

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



A good metaphor for the comparison of relative ionising power is shown in the picture below:



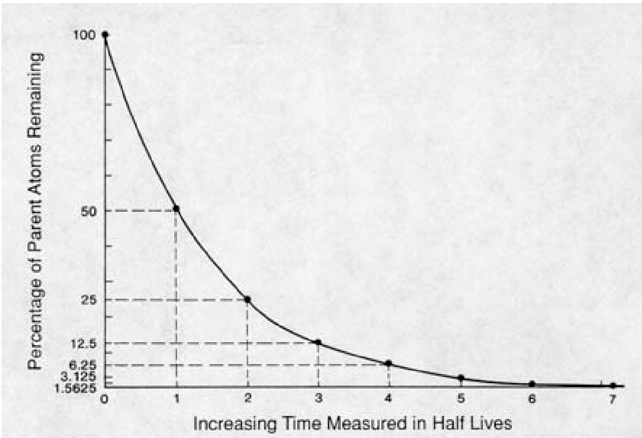
A smoke alarm uses an alpha source. Explain how this source works to activate the klaxon when a fire is present.

Three separate rooms (10m by 10m) have a radioactive source mounted in the middle of each room. Each room has a different source – one has an alpha source, one has a beta source, and one has a gamma source. Each produces an equal number of particles per hour. You have to stay in one of these rooms for 12 hours. Which room would you choose and why?

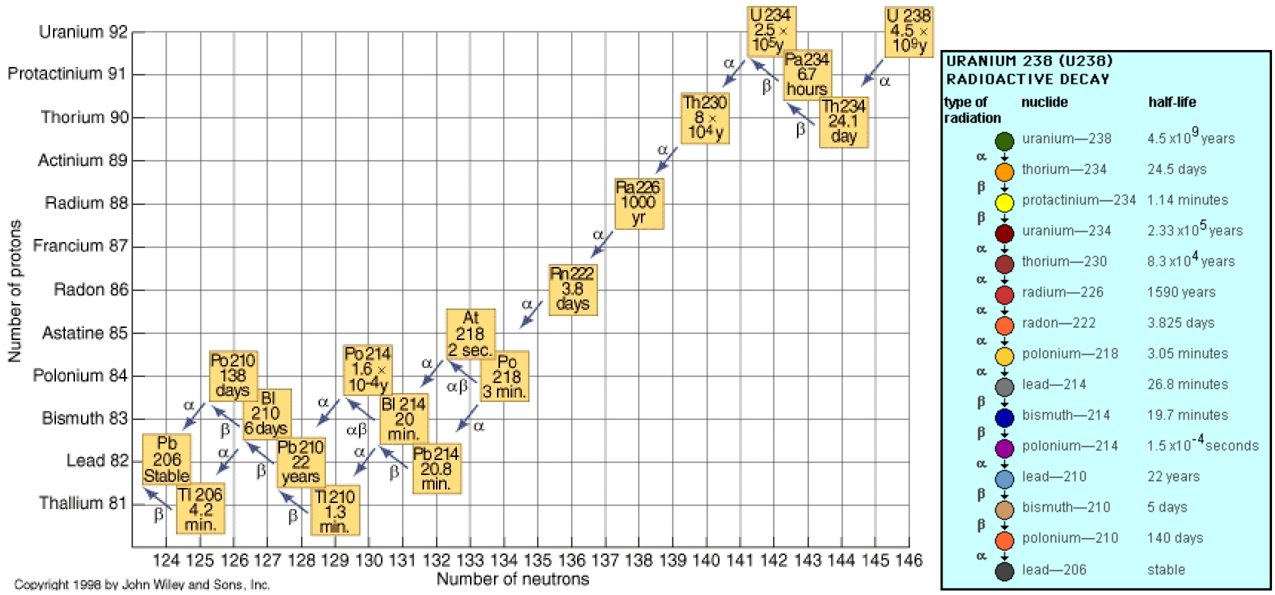
	Topic	Heinemann (H) and Jacaranda (J)		
		Section	**Pages**	**Questions**
3.	**Half-life and activity**	**Half life**	**H141**	**1-10**
			J23	**17, 23 - 29**
		Decay Sequences	**H130**	**4 - 9**
			J23	**18 – 19, 21 – 22,**

Part 3: Half-life and activity

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 ($T_{1/2}$) 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. At any particular point, the number radioactive particles remaining are determined by the following formula:

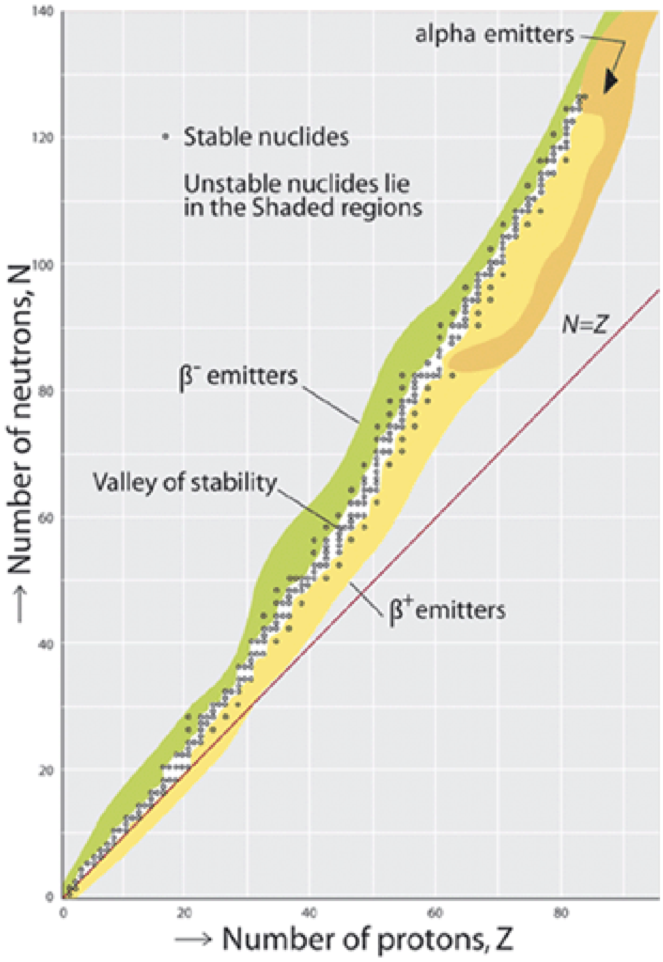
$$N = N_0 e^{-\lambda t} \qquad \begin{aligned} N &= remaining\ \ atoms \\ N_0 &= initial\ \ atoms \\ \lambda &= decay\ \ const. \\ t &= number\ \ of\ \ halflives \end{aligned}$$

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

The table above shows the half-life of a number of different radioactive isotopes. Which of these isotopes has the highest activity (greatest rate of decay)?

Which of these isotopes is the most radioactive, given equal masses of each are available?

Which of these isotopes is the most difficult to dispose of in radioactive storage?



The diagram to the right shows the different types of decay that occur to particular isotopes. As you can see, the "valley of stability" where nuclei are non-radioactive, between the different unstable regions, increases its gradient above the N = Z line. This shows that as an element has a higher atomic number (more protons) it needs increasing numbers of neutrons to ensure the stability of the nucleus.

<u>Activity</u>

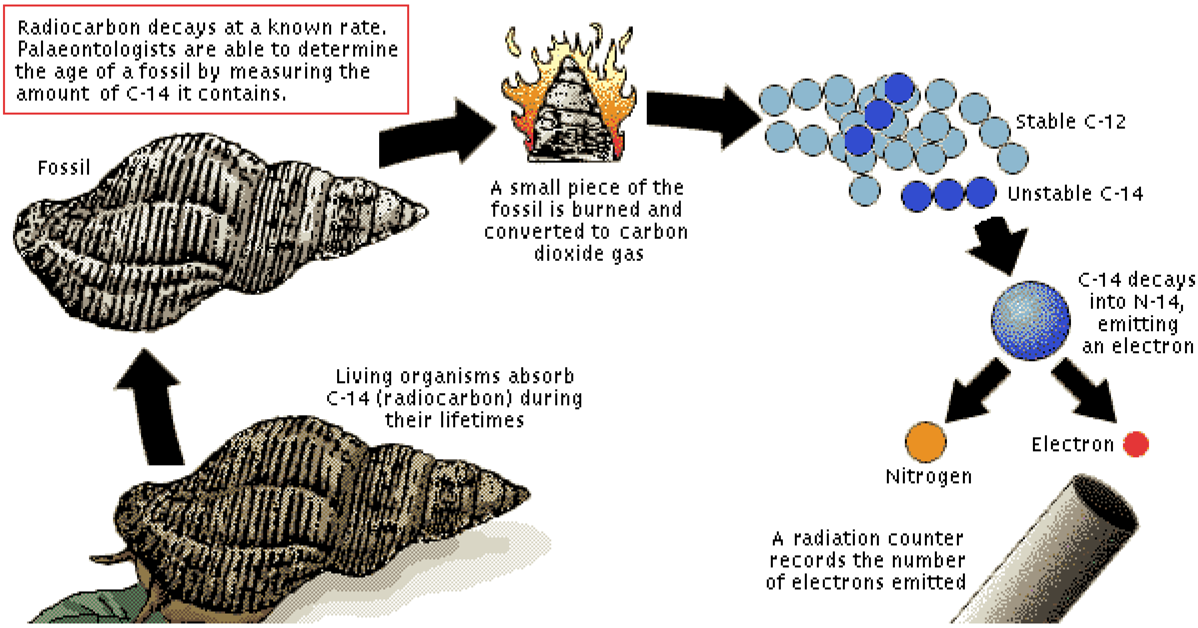
The strength of any given radioactive source is determined by its activity. The activity of the sample indicates the number of radioactive decays that are occurring in the sample each second. Activity is measured in Becquerels (Bq), where 1 Bq = 1 disintegration per second. The activity of any radioactive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

Radioactive decay can be a useful tool to science, despite the dangerous side effects. As indicated in table at the top of the page, radioactive isotopes can have practical uses. Aside from the obvious energy generation possibilities, the radiation that comes from the decay process can have useful applications to amongst others, medical imaging, sterilisation and industrial control procedures. Beyond these uses, the known rate of decay of radioisotopes can be used to measure the age of objects. One of the primary techniques is called radiocarbon or carbon-14 dating. The diagram below explains this process.

Alchemists sought to transform lead into gold using a chemical reaction involving a mythical substance called "The Philosopher's Stone". What is the nuclear difference between a gold atom and a lead atom (use the most common isotopes)?

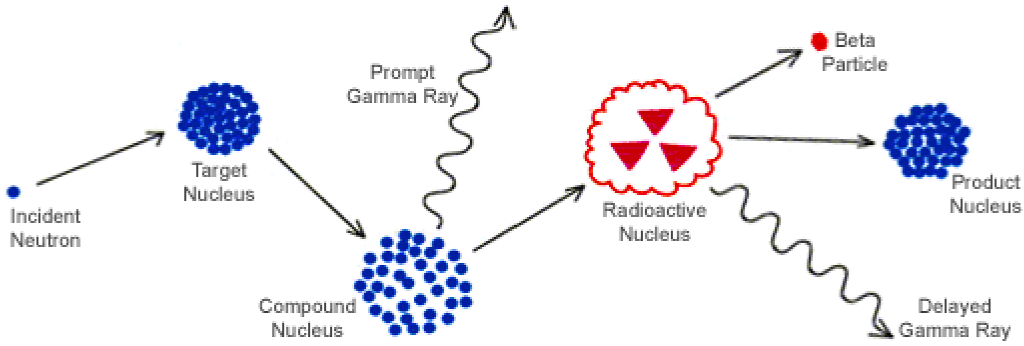
Explain why this transformation cannot occur in a chemical reaction

Propose a sequence of nuclear reactions that could result in lead turning into gold (non radioactive!)



By comparing the activity of the sample to the predicted level the sample would have had before death, the number of half lives that have passed since death can be determined. Carbon 14 has a half life of 5730 years, which means that carbon dating is only effective for samples of a maximum of 60000 years of age. The accuracy of the technique is limited to a range of ±40 years.

To make artificial radioisotopes, a target nucleus is bombarded with neutrons. The nucleus may absorb one of these neutrons, becoming unstable in the process. This will usually result in a beta decay, causing the atomic number to increase by one, creating a new element to be formed.



	Topic	Heinemann (H) and Jacaranda (J)		
		Section	Pages	Questions
4.	Effects of Radiation on Living Organisms	Irradiation effects	H147 J25	Q1-10 Q30 - 43

Part 4: Effects of Radiation on Living Organisms.

Background Radiation

Every living organism is exposed to radiation every single day; we call this radiation Background radiation, and it comes from three primary natural sources:

1. Radiation from terrestrial sources:
    a. Decay of radioactive materials in the Earth's crust
    b. Radioactive gasses in the Earth's Atmosphere
2. Radiation from extraterrestrial sources, such as cosmic rays.

A small part of the background radiation is artificial in origin, coming from modern industry, but this forms less than 6% of the total. Most of this artificial background radiation comes from older coal-fired power plants. Other exposure to radiation can come from medical imaging procedures such as X-rays and PET scans; this can add up to a further 50% to the average human exposure[4].

Additional Exposure

Exposure to other sources of radiation can cause dangerous effects, depending on the amount absorbed and the type. The absorbed dose is measured in units called grays (Gy), which one joule per kg

$$1 \ Gray = \frac{1 \ J}{1 \ kg}$$

This is called the "absorbed dose". It reflects the amount of radiation an organism has been exposed to. However, as explained in the above notes, type of radiation also has an effect. An equivalent energy amount of Alpha radiation would do far more damage than the same energy amount of gamma radiation, as is shown by the relative ionising power. To reflect this fact, we can also calculate the effective dose which is measured in a unit called sieverts (Sv). The effective dose in sieverts is calculated by multiplying the absorbed dose by the quality factor, which is determined by the type of radiation.

Radiation Quality Factors	
Radiation type	QF
Alpha (α)	20
Beta (β)	1
Gamma (γ)	1
Fast Neutrons	5-20

[4] United Nations report on the Effects of Atomic Radiation: http://www.unscear.org/docs/reports/gareport.pdf

$$effective\ \ dose\ = \ absorbed\ \ dose\ \times\ quality\ \ factor$$

This applies only to whole body (human) exposure. Humans are very vulnerable to radiation compared to other organisms; for example, bacteria can tolerate doses of radiation 3000 times that which would kill a human. This relative vulnerability factor is called the N-Value, and is summarised in the following table.

N – Values for particular Human organs		N-Value ranges for other organisms	
Organ	N-Value	Organism	N-Value Range
Gonads	0.2	Plants	2 – 0.2
Bone marrow, colon, lung, stomach	0.12	Humans	1
Other internal organs	0.05	Reptiles	1 – 0.75
Bone surface, Skin	0.01	Fish	0.75 – 0.03
		Birds	0.6 – 0.15
		Amphibians	0.4 – 0.14
		Viruses	0.03 – 0.0003

For Human whole body exposure, the following table indicates the possible effects and likely fatality (survival duration).

Human Whole Body Effective Dose effects		
Amount (Sv)	Effects	Lethality
<0.2	No recognised symptoms. Doses below this amount are often used in medical practice	<1%
0.2 – 0.5	No physical symptoms; Red blood cell count drops	<1%
0.5 – 1.0	*Mild Radiation Sickness.* Some disruption of immune system with associated chances of contingent infections/ illness. Possible temporary male sterility	<1%
1.0 – 2.0	*Light Radiation Poisoning.* Nausea and general delocalised feelings of illness and fatigue. Severe immune system disruption. Spontaneous abortion or stillbirth in pregnant females	≈10% (30 days)
2.0 – 3.0	*Moderate Radiation Poisoning.* Severe Nausea and vomiting Complete disruption of immune system (99% of white blood cells destroyed) Total body hair loss (50% of cases) Possible permanent female sterility	≈35% (30 days)
3.0 – 4.0	*Severe Radiation Poisoning.* Severe Nausea and vomiting Complete disruption of immune system (99% of white blood cells destroyed) Total body hair loss Possible permanent female sterility Uncontrollable bleeding from mouth, under the skin and kidneys	≈50% (30 days)
4.0 – 6.0	*Acute Radiation Poisoning.* As above but also Likely permanent female sterility Uncontrollable internal bleeding	60 – 90% (14 – 30 days)
6.0 – 10.0	*Extreme Radiation Poisoning.* As above, but also complete destruction of bone marrow and gastrointestinal tract. Survivable with extensive medical support.	100% (14 days)
10.0 – 50.0	*Fatal Radiation Poisoning.* Symptoms onset within 5 – 30 minutes; extreme fatigue and nausea Total cell death; breakdown of circulation. “Walking Ghost” phase	100% (7 days)
>50.0	*Immediately Fatal Radiation Poisoning.* Events to rare to generalise effects	100% (49 hours)