Physics Factsheet

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Nuclear Medicine Used For Treatment

Factsheet 'Nuclear medicine used for treatment	Factsheet, 'Nuclear medicine used for diagnosis'
• biological effects of ionising radiation	• production of radionuclides
• use of nuclear radiation in the treatment of illness	• using radionuclides for imaging
	• measurement of exposure to radiation

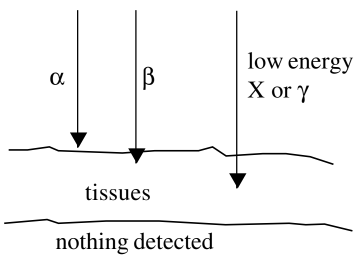
Although X-rays are indistinguishable from γ-rays of the same energy,

they do not come from the nucleus and so have not been **specifically** included. **However,** all calculations would be identical.

What you should know

properties of:
- α, ✓
- β ✓
- γ ✓ → Factsheet 11 and Qus 1 & 2 on this factsheet
- calculation of half life $T_{½}$✓

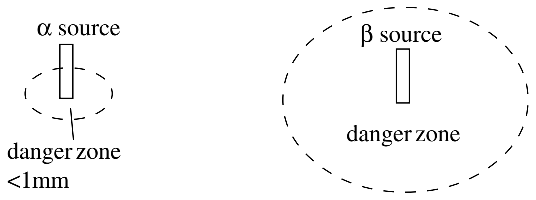
α, β and **low energy X** and γ-rays are called '**non-penetrating**' because they do not pass through tissue.



They are **not** used in **diagnosis** but are useful in **therapy.**

> *Therapy* ***is treatment to try to make the patient well.***

The purpose of nuclear medicine in therapy is usually to kill cancerous cells. α and β radiation may be used close to the tumour. They are highly ionising with a short range so that too many healthy cells are not damaged.



Alternatively several beams of γ may be arranged to cross where cells need to be killed.

> ***Exam Hint : -*** *As always read the question carefully. Very few marks would be obtained if you wrote about* ***diagnosis*** *when the question asks for* ***therapy****. Sometimes they can be opposite, for example β rays are useful in killing tumour cells but should be avoided inside the body at all other times.*

Biological Effects of Radiation

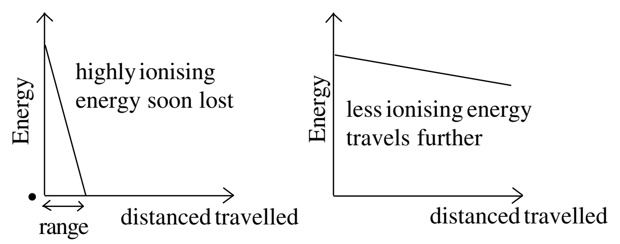
Damage is mainly caused by **ionisation.**

> ***Ionisation*** *is the removal of electrons from atoms.*

α and β particles move at high velocity and can easily knock electrons out so they are called **ionising radiation**.

> ***Ionising radiation*** *is a beam of high energy particles (waves are not so highly ionising) that will remove one or more electrons from an atom in its path.*

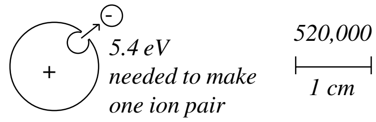
Each time ionisation occurs the kinetic energy of the particle is reduced, so the greater the ionisation the shorter the **range** (distance travelled before coming to rest).



α radiation is extremely dangerous if it gets inside the body e.g. in the lungs, β is to be avoided unless it is needed to kill cells.

Worked Example

It takes 5.4 eV to create an ion pair and an α particle creates 5.2×10^5 ion pairs per cm of air.



The range of α's from a certain source is 2.9 cm, what was their energy in eV when they started?

Total energy $= 2.9\ cm \times 5.2\times10^5\ cm^{-1} \times 5.4\ eV$

$= 8.1\ MeV$

γ and X rays are high frequency, short wavelength (less than 1 nanometre), electromagnetic radiation. Each photon can remove an electron if it has high enough energy so they may also be considered as **ionising radiation**. It is the energy that is important so that is how they are described e.g a 2.0 MeV X ray.

$E = hf = hc/\lambda$

Worked example
Find the wavelength of a 0.35 MeV γ ray
0.35×10^6 eV = $0.35\times10^6 \times 1.6 \times 10^{-19}$ J = 5.6×10^{-14} J

$$E = \frac{hc}{\lambda} \therefore \lambda = \frac{hc}{E} = \frac{6.6\times10^{-34}\times3\times10^{8}}{5.6\times10^{-14}} = 3.5\times10^{-12}\,m$$

Ultra-sound, lasers and magnetic resonance imaging (MRI) ***do not*** *involve ionising radiations at all and so should be safer.*

Computer Tomography (CT) scans use X-rays.

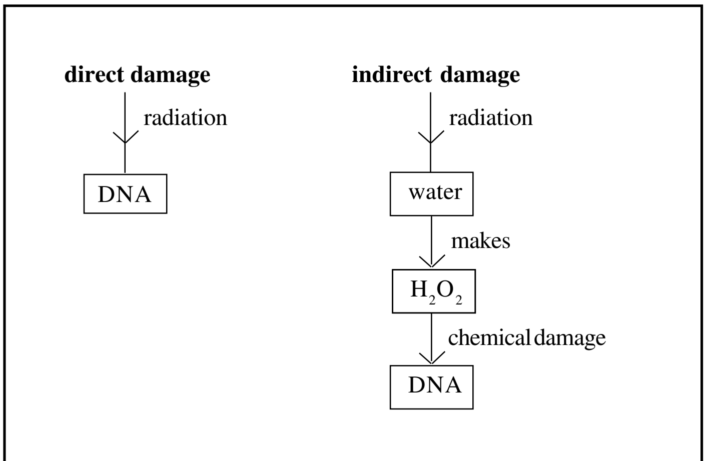
Ionising radiation	Non Ionising radiation
α -highly	Ultra sound
β –slightly less	Laser
high energy γ & X rays - less	Magnetic resonance imaging MRI

Details of damage

Exam Hint:- This section is full of pairs of words,
macroscopic - microscopic
direct - indirect
stochiastic - non-stochiastic
somatic - hereditary
Make sure you know what each means and try to work out which ones are relevant to the question.

Direct damage:
The radiation may **directly** ionise an atom in an important molecule within a cell such as enzymes, DNA or RNA. DNA is particularly important. The cell will no longer function normally and cell death or mutation may result.

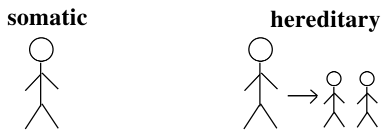
Indirect damage
If water molecules in the cell are split into OH^- and H^+, hydrogen peroxide (H_2O_2) may form from two OH^-. The hydrogen peroxide may **then** damage the DNA in the chromosomes of the nucleus and the cell may die or be unable to reproduce. This is **indirect** damage because there is an extra stage. The cell wall permeability is often affected.



These are **microscopic** events. Larger scale or **macroscopic** effects are: Uncontrolled cell division (cancer) may result from either direct or indirect damage. Organs may fail, e.g. bone marrow, or may be destroyed, e.g. in skin burns. Genetic abnormalities increase.

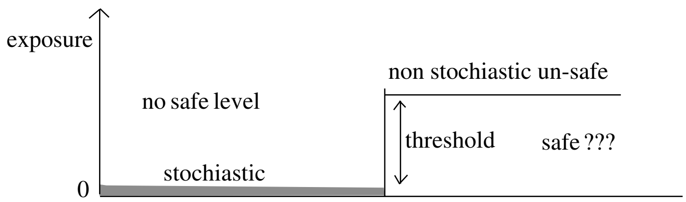
microscopic	macroscopic
direct damage in cell indirect damage in cell	cancer organ failure e.g. bone marrow destruction of tissue, skin burns, genetic abnormalities

If the reproductive organs are affected then the effect may be passed on to the next generation. This is then **hereditary** damage as distinct from **somatic** which just affects the individual.

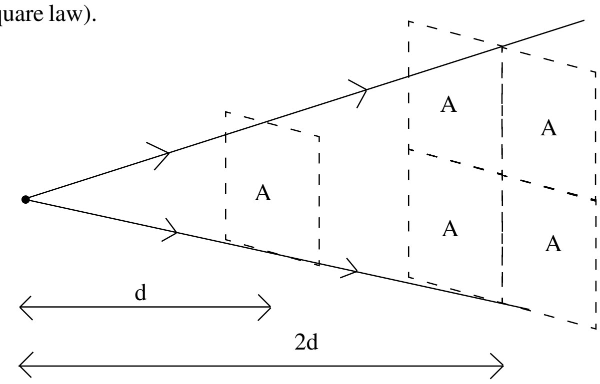


Some damage may be started by just **one** event, e.g. cancer or mutation. This type is called **stochiastic** (meaning random). There is no safe level of irradiation.

Other effects may not be noticeable unless a certain level called a **threshold** is reached e.g. skin burns. These are **non-stochiastic.**



Protection
The effect of ionising radiation is reduced by keeping your distance. If you double the distance then the effect goes down to one quarter (inverse square law).



Exam Hint: - *The inverse square law always applies where there is little absorption in the medium, e.g. sound, gravity, γ and X rays in air.*

$$I \alpha \frac{1}{d^2} \text{ or } \frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$$

Worked Example
A ^{60}Co source provides an exposure rate of 270 μCkg^{-1}s^{-1} at a position 1.0 m in front of it. Estimate the exposure rate 3.0 m away from the source ignoring any attenuation in the air.

The new position is 3 times farther away
so the new exposure rate will be 1/9 (1/ 3^2) of the value at 1.0 m.
Exposure rate = 270/9 = 30 μCkg^{-1}s^{-1}.

Absorption of radiation

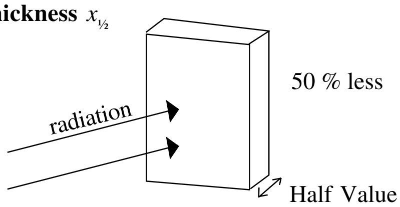
Shields may be used and the intensity in an absorber follows an exponential decrease. The same equation is used for X rays or γ rays.

> $I = I_o e^{-\mu x}$
>
> *I = intensity after travelling distance x in the material.*
> *I_o = original intensity (NOT to be confused with the I_o in sound which has value 1×10^{-12} W m^{-2} and is the zero level of sound that can be heard).*
> *e = linear attenuation coefficient. It is a property of the material but also depends on the energy of the incident photons.*
> *x = distance travelled in or the thickness of the material.*

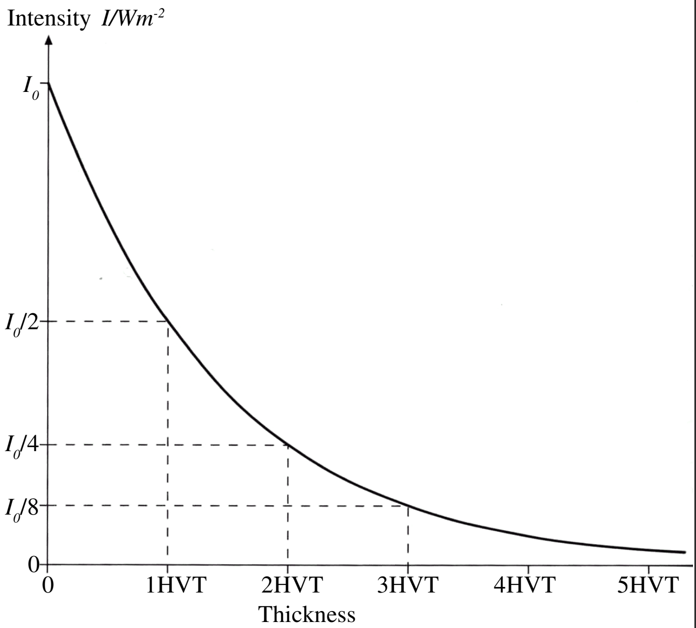
Exam Hint:- the exponent (number up in the air) is always dimensionless so if x is in cm then μ is the inverse and is cm^{-1}.

> ***Worked Example***
> ***A parallel monoenergetic γ-ray beam passes through 3.0cm of a material. The intensity of the emerging beam is 0.60 of the original. Calculate a value for μ.***
>
> *$I = 0.60\ I_o$*
> *$0.60\ I_o = I_o\ e^{-3.0\mu}$ (I_o cancels and you don't need to know it.)*
> *take **natural** logs both sides, **ln** (not log, that's to base 10 not to base e)*
> *$\ln 0.60 = -3.0\ \mu$*
>
> so $\mu = \dfrac{\ln 0.60}{-3.0} = \dfrac{-0.51}{-3.0} = 0.17$ cm^{-1}

For each type of material and energy of the radiation there will be a **Half-Value-Thickness** $x_{½}$

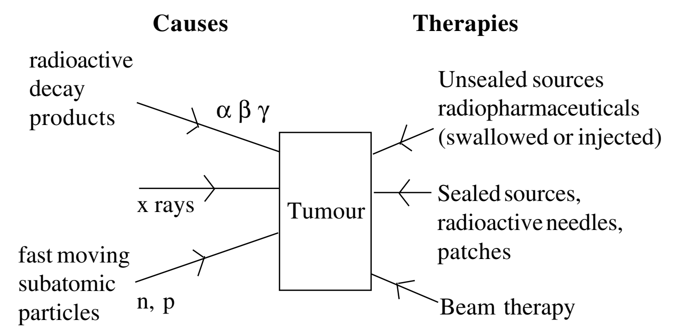


> *The **half-value-thickness** is the thickness of material required to reduce the **intensity** of the radiation to **one half** the original value.*
> $x_{½} = \dfrac{0.693}{\mu}$ *(compare with half-life equation Factsheet 11)*



> ***Worked Example***
> ***80 keV γ rays have μ = 690 m^{-1} in copper.***
> ***(a) Calculate the half value thickness***
> ***(b) use this answer to find the fraction remaining after travelling through 3.0 mm.***
>
> (a) $x_{½} = \dfrac{0.693}{\mu} = \dfrac{0.693}{690} = 1.0\times10^{-3}$ m or 1.0 mm
>
> *(b) it halves each time it goes through 1.0 mm so 1/8 remains.*

Types of therapy



The guiding principle is always that there is **no** safe dose. All doses should be kept as low as possible and there should be **positive benefit** from **any** exposure.

Exposure is mainly concerned with killing cancerous cells. Luckily dividing cells are more radiosensitive than non-dividing. So as cancer cells are dividing rapidly there is a chance of killing them.

A. Unsealed sources
These can only be used if they accumulate in the organ that needs treatment. A radionuclide is attached to a pharmaceutical (making a radiopharmaceutical) and the liquid is injected or swallowed.
In the thyroid radioactive Iodine taken orally is used to counteract overactivity (with a smaller dose than if cancer is present.)

The behaviour of a nuclide introduced into the body

Effective half life of a radioactive substance
As well as the usual reduction in activity with time, **physical half-life T_p**, the chemical may be reduced by bodily processes and waste removal or respiration. This decrease is also exponential so it has a half-life T_b known as the **biological half-life.** This varies with the individual and the organ involved but taking both into account, the **effective half-life T_e** is given by

> $$\frac{1}{T_e} = \frac{1}{T_b} + \frac{1}{T_p}$$

> ***Worked Example***
> *The physical half life of Iodine 123 is 8.0 days and it is removed from the body with a half life of 21 days.*
>
> $\dfrac{1}{T_e} = \dfrac{1}{T_b} + \dfrac{1}{T_p} = \dfrac{1}{21} + \dfrac{1}{8} = 0.0476 + 0.125 = 0.173(d^{-1})$
>
> *don't forget this is still* $\dfrac{1}{T_e}$
>
> $\therefore T_e = 5.8$ *days*

Typical Exam Question

(a) What is meant by the terms (i) radioactive half life (ii) biological half-life? (2)

(b) Why does biological half-life depend upon both the organ and the patient? (2)

(c) Iodine-131 has a half-life of 8 days. Approx. what % will remain in the body after 1 month. (there is no mention of biological half life so take the question at face value) (2)

(d) Complete the equation below (2)

$^{131}I \rightarrow {}_{54}Xe + \beta + \gamma$

(e) Another isotope of iodine I-123 is available which decays by emission of gamma only. Explain which you would choose for the treatment of the thyroid by ingestion. (3)

Answers

(a) (i) the average time for half the nuclei to decay or the activity to fall to ½ the initial value. (1)
*(NB some exam boards **insist** on the word **average** somewhere because of course they are random processes)*

(ii) the average time for half the chemical to be metabolised or excreted from an organ. (1)
(NB this has nothing to do with radioactivity, it applies to any chemical)

(b) Different organs will metabolise the chemical at different rates. Different patients will have different overall metabolic rates which also depends on what they are doing at the time.

(c) There are about 4 half lives (1)
in 1 month so at the end of each half-life there will be 1/2,1/4,1/8,1/16. 1/16 is about 6% (1)(OK to only have 1 sig fig if it says approximately)

(d) a neutron will have changed to a proton and an electron which is ejected.

$${}^{0}n \longrightarrow {}^{+1}p + {}^{-1}e + {}^{0}v$$

The charge number for I must be 53 (1),
the mass number for Xe is the same at 131 (1)

(e) I would choose I-131. (1) (make sure you say what you mean)
I-123 would be no use, all the radiation would leave the body.
The β is needed (1)
to damage unwanted tissue.(1) (don't forget to explain WHY)

B. Sealed Sources

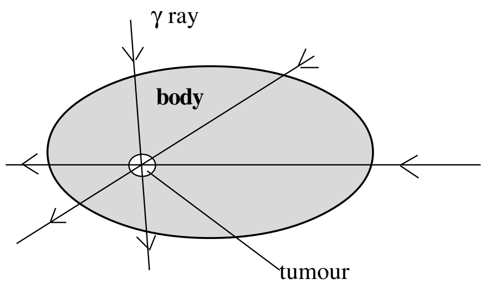
The source of radiation needs to be as close as possible to the tumour to avoid damage to healthy cells. This may be achieved by surface patches, inserting needles into the skin, or containers into body cavities. β emitters are used for short range work. New ideas include inserting tubes into the body and then blowing the radionuclide into them.

When it is not possible to get close, longer range X, γ or electron beams are used. Cobalt-60 may be used as a source of γ rays of energy of about 1.25 MeV. It is hard to control (the energy cannot be varied, the source cannot be switched off and the beam is not well defined) and the other types of radiation are generally preferred.

Co-60	No on/off switch No energy adjustment No focusing knob
X-ray	On/off switch ✓ Energy adjustment ✓ Focusing with difficulty ✓

Hospitals are introducing linear accelerators to produce high energy X-ray beams.

In order to reach the target tumour, healthy tissue must be crossed. To reduce the damage done on the way in, **Multiple beam therapy** may be used where several beams cross at the target



or the source may rotate so that the target always receives the radiation. This treatment may be called a **gamma knife**.

It is common to split the dose up into fractions and administer them over a period of some weeks. Healthy cells recover more quickly than cancerous ones.

A cell which was not dividing the first time may be caught the next time, the odds are higher that a cancerous one will be caught.

Unfortunately the dose that the tumour receives is **critical,** a small reduction makes the treatment ineffective and a small increase may do harm.

dose too small	**dose just right**	**dose too large**
cancer cells not all killed	all cancer cells killed and not too many healthy cells	too many healthy cells killed as well

Qualitative (concept)Test - answers to be found in the factsheet

1. In the equation $I = I_0 e^{-\mu x}$, for the decrease in intensity of radiation passing through a material, state the name of the constant μ.

2. List 2 factors which affect the value of μ.

3. Why are α and β radiation sometimes used in therapy but never in diagnosis?

4. What is meant by ionising radiation?

5. Under what condition does the intensity of radiation decrease following an inverse square rule?

6. In the equation for decay of radioactive atoms, $N = N_o e^{-\lambda t}$, if t is in seconds then what must be the unit of λ?

Quantitative (calculations) test

1. An α source of activity 30Bq gives an ionisation current of 2.2×10^{-11}A.

   (a) How many singly charged ions per sec is this?

   (b) How many ions on average does each a particle cause?

2. Sample X and Y have the same number of atoms. The half-life of X is 10 mins and that of Y 20 mins. What is the ratio of activity X to activity Y:
   (a) at the start

   (b) after 20 mins?

3. With a source of Co^{60} the γ dose rate is 80 μSvh^{-1} at 2.0 m away. At what distance will it be 20 μSvh^{-1}?

Exam workshop
This is a typical poor student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiner's mark scheme is given below.

(a) Ionising radiation is incident on living matter. Explain with an example, the terms

(i) direct effect **[2]**

skin burn ✓ *1/2*

no explanation, first mark lost

(ii) indirect effect **[2]**

releases free radicals ✓ *damaging cells* *1/2*

needs to be specific about the effect of the free radicals – too vague to get the second mark

(b) (i) explain why cancerous cells may be killed at a greater rate than healthy ones. **[2]**

healthy cells recover more quickly ✗ *0/2*

although true this does not explain why cancerous cells are more likely to be killed, no marks.

(ii) Explain a method to treat a tumour but keep damage to healthy cells low **[3]**

the beam is focused on the tumour. other areas are shielded.✓ bod

It is not possible to 'focus' the beam.
It still passes through healthy tissue which receives the same dose as the tumour. The material used for shielding should be named. This **might** be awarded a benefit of the doubt mark at the examiner's discretion.

Examiner's answers

(a) (i) the radiation ionises the DNA (1)
this leads to mutation/ cancer or the death of the cell (1)

(ii) The interaction of the radiation splits water in the cell into H^+ and OH^- / or free radicals, this may form hydrogen peroxide H_2O_2 (1) The DNA is damaged or the permeability of the cell membrane affected.(a mark for mention of cancer or mutation is only allowed once in the two parts)

(b) (i) radiation is most harmful to cells when dividing (1)
malignant cells divide more often than normal cells (1)

(ii) there are about 4 possible methods here. It is best to select one and describe it thoroughly. You cannot gain 3 marks for naming 3 different methods and be careful about a mixture of 2.

1st mark	*2nd mark*	*3rd mark*
source of radiation rotated/multiple beams used	*tumour at centre*	*tumour gets larger dose than healthy nearby tissue*
lead shielding is placed around the area	*this stops the radiation except for a hole over the target*	*the tumour is targeted*
a small dose called a fraction is repeated at interval	*healthy cells recover faster than cancerous ones*	*there is more chance of catching a cancerous cell dividing*
a radioactive substance is put near the tumour	*it must be α or β* ***or*** *have a short half life*	*because short range* ***or*** *to quickly stop the damage*

Quantitative test answers

1. (a) $I = \frac{Q}{t} = \frac{Ne}{t} \therefore \frac{N}{t} = \frac{Q}{et}$

   the number of ions per sec is the current divided by the charge on one ion

   $N = \frac{2.2 \times 10^{-11}}{1.6 \times 10^{-19}} = 1.4 \times 10^{8}$ singly charged ions per sec are produced

   (b) 30 Bq means 30 particles per sec so $\frac{1.4 \times 10^{8}}{30} = 4.7 \times 10^{6}$ ions from each particle.

2. Activity, A = λN, and λ is inversely proportional to the half-life,

   $\lambda = \frac{0.693}{T_{½}}$

   the half-life of X is half that of Y so the decay constant of X will be twice that of Y

   $\lambda_x = 2\lambda_y$

   $A_x = \lambda_x N = 2\lambda_y N = 2A_y$ so at the start the ratio of the activities is 2 .

   After 20 mins. X has N/4 atoms and Y has N/2,

   $\frac{A_x}{A_y} = \frac{2\lambda_y \frac{N}{4}}{\lambda_y \frac{N}{2}}$ =1 so the ratio is now one.

3. If you double the distance away the dose will be one quarter which is what is required. So 4.0m.

Acknowledgements:
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