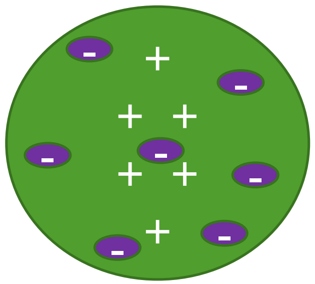
Nuclear physics

A-level overview

isaacphysics.org
https://isaacphysics.org/pages/remote_learning

Atomic models

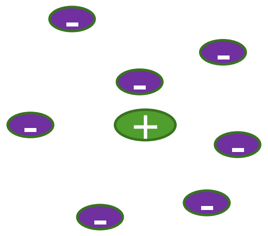
Plum pudding

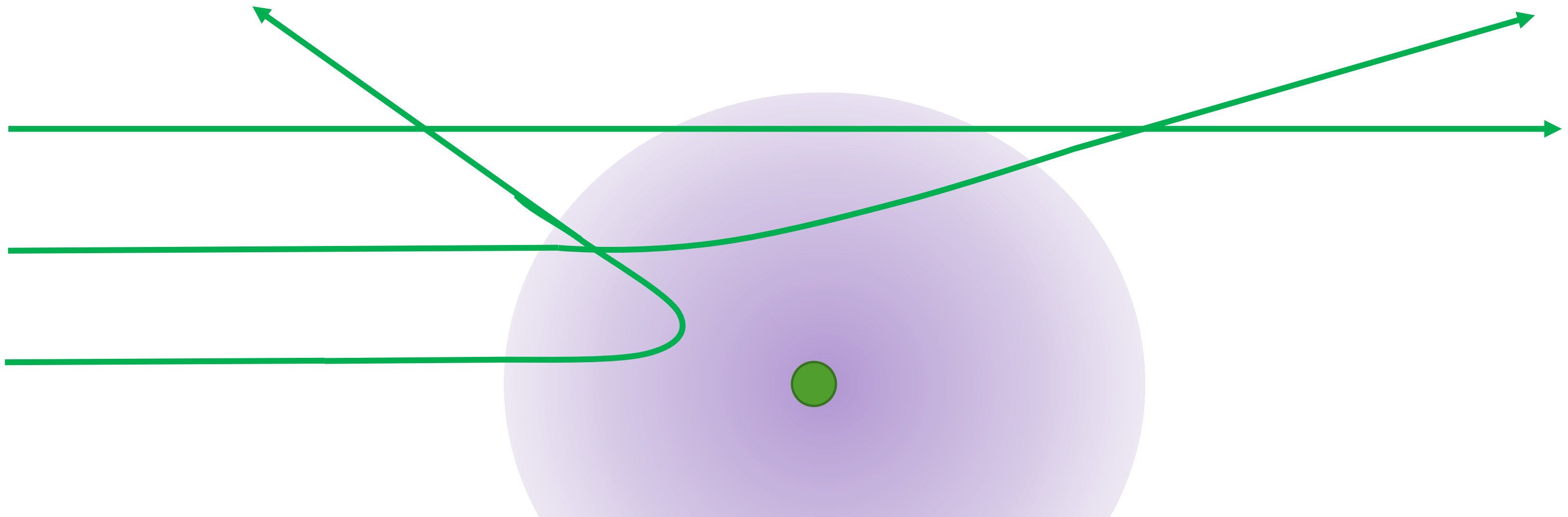


Scattering

Alpha particles fired at the atom usually did not deflect. A small number were bounced back.

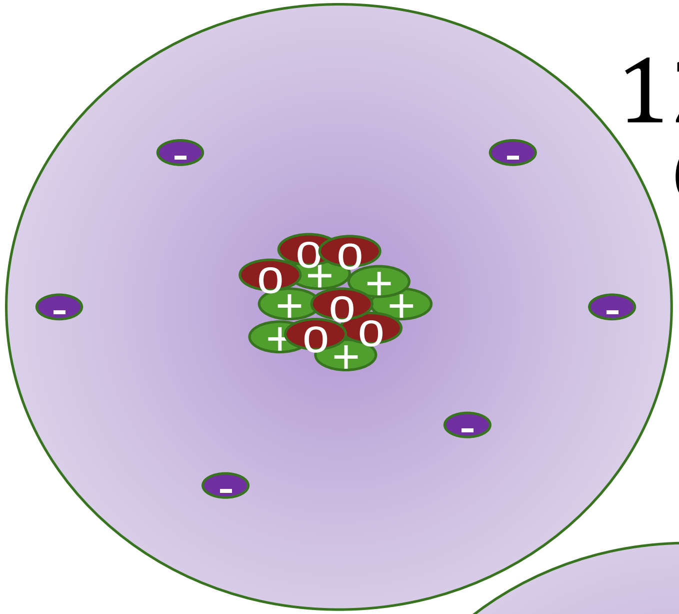
Nuclear





Meet the atom

Particle	Charge (C)	Mass (kg)
Proton	$+1.6 \times 10^{-19}$	1.67×10^{-27}
Neutron	0	1.67×10^{-27}
Electron	-1.6×10^{-19}	9.11×10^{-31}
Positron	*$+1.6 \times 10^{-19}$*	*9.11×10^{-31}*
Specific charge Ckg^{-1}= charge / mass		



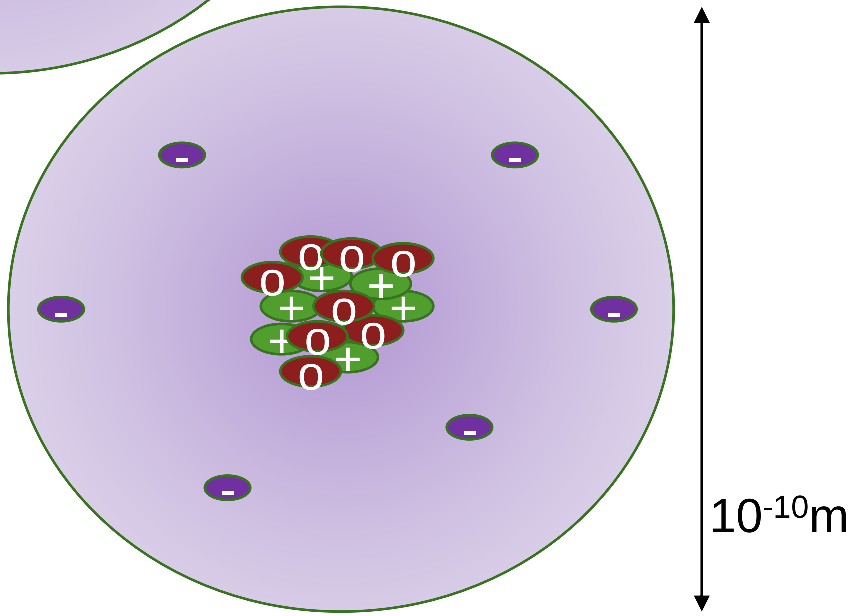
$^{12}_{6}C$

Same element
Different mass
ISOTOPES

Mass of nucleus (or atom) approx. proportional to number of neutrons and protons (mass number)

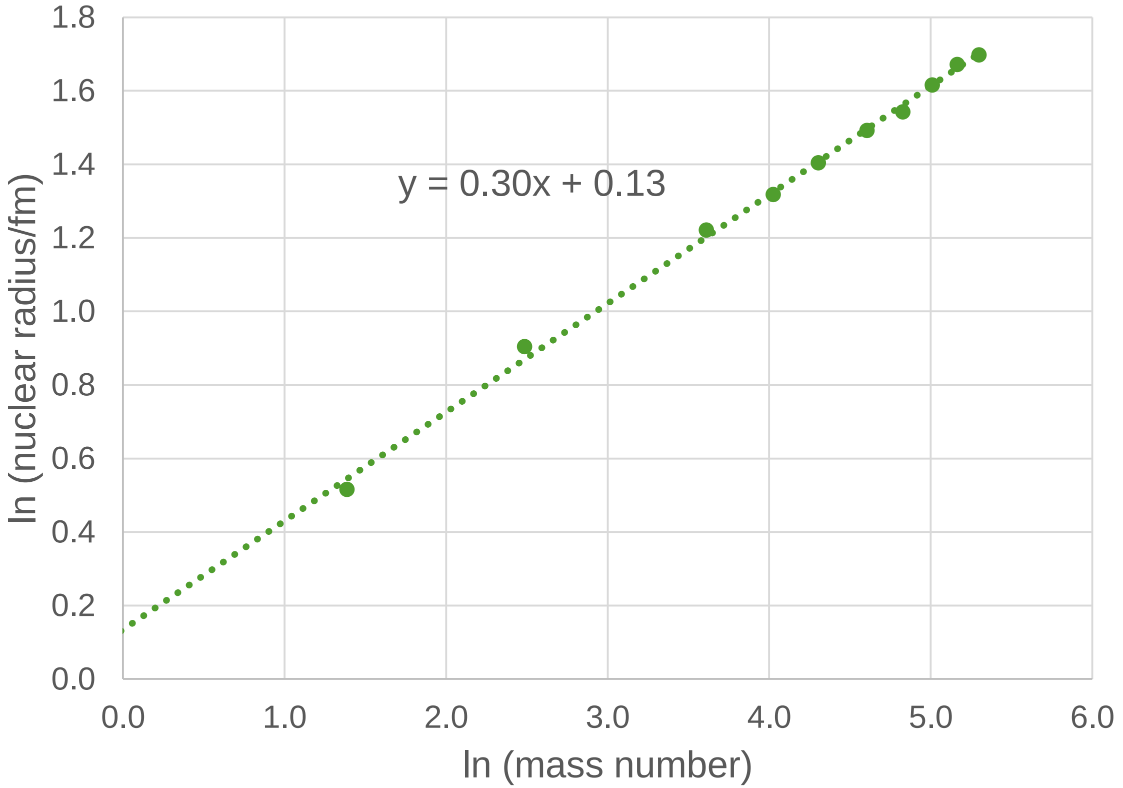
$^{14}_{6}C$

Charge of nucleus proportional to number of protons (atomic number)



Nuclear radii

A	r/fm	ln A	ln (r/fm)
4	1.68	1.39	0.52
12	2.47	2.48	0.90
37	3.39	3.61	1.22
56	3.74	4.03	1.32
74	4.07	4.30	1.40
100	4.45	4.61	1.49
125	4.68	4.83	1.54
150	5.03	5.01	1.62
175	5.32	5.16	1.67
200	5.46	5.30	1.70



Nuclear radii are measured using electron diffraction

The volume is approximately proportional to the mass number

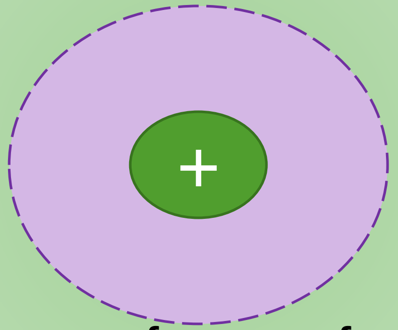
$$r = r_0 \sqrt[3]{A} \qquad r^3 = A r_0^3 \qquad r_0 = 1.1 \times 10^{-15}\mathrm{m}$$

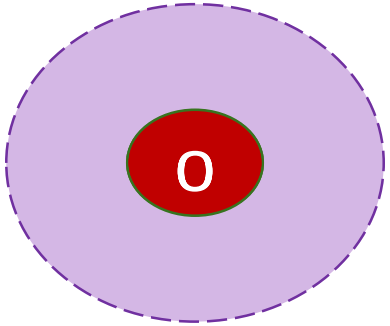
Strong nuclear force

Holds nucleons (protons & neutrons) together in the nucleus

Short range (<4fm), but within that range, stronger than electromagnetism

Becomes repulsive if <0.5fm





Nuclide practice

1. How many protons, neutrons and electrons are there in these nuclides? ${}^{2}_{1}H,\ {}^{3}_{1}H, {}^{15}_{8}O, {}^{56}_{26}Fe, {}^{238}_{92}U$

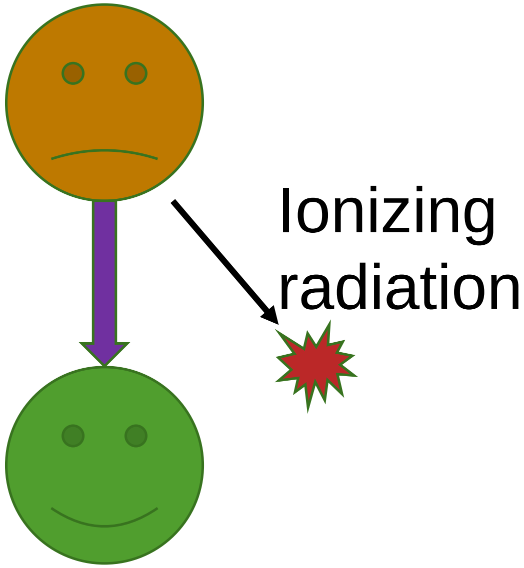
2. Write the symbol for the isotope of...
   a) carbon (6) with 7 neutrons
   b) hydrogen (1) with no neutrons
   c) neon (10) with mass number of 21

3. Calculate the specific charge of a ${}^{56}_{26}Fe$ nucleus

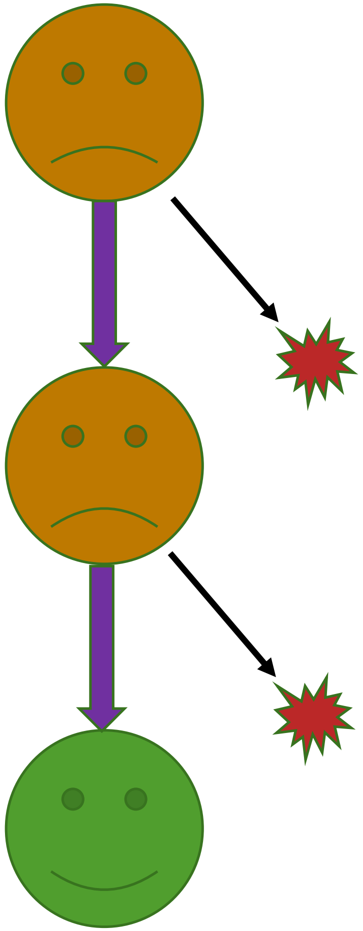
Ionizing radiation

Stable nucleus

Unstable nucleus



Stable nucleus



When ionizing radiation passes another atom, it will take out electrons. The atom’s chemistry will be altered.

This makes ionizing radiation harmful to life

Types of radiation

$$^{241}_{95}\mathrm{Am} \rightarrow \mathrm{Np} + {}^{4}_{2}\alpha$$

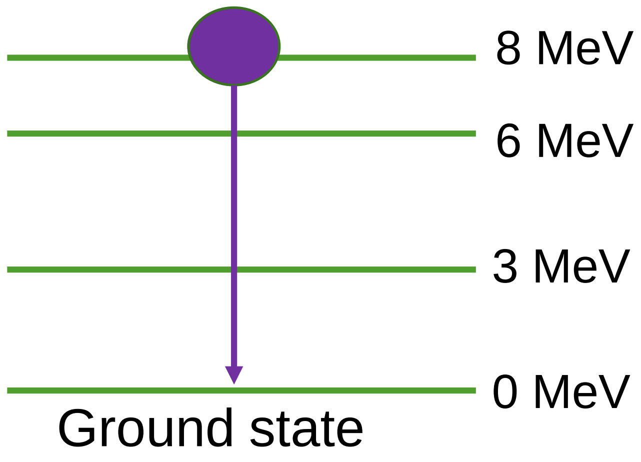
$$^{14}_{6}\mathrm{C} \rightarrow \mathrm{N} + {}^{0}_{-1}\beta + \overline{\nu}_e$$

$$^{11}_{6}\mathrm{C} \rightarrow \mathrm{B} + {}^{0}_{+1}\beta + \nu_e$$

$$^{99}_{43}\mathrm{Tc} \rightarrow \mathrm{Tc} + {}^{0}_{0}\gamma$$

	What it is	Range in air	Stopped by	Ionizing?
Alpha	helium nucleus (2p+2n)	5cm	paper skin	very
Beta -	high energy electron	1m	1cm Al	moderately
Beta +	high energy positron		anything	N/A annihilates
Gamma	high freq. electromag. wave	far	few cm Pb	weakly

Gamma decay

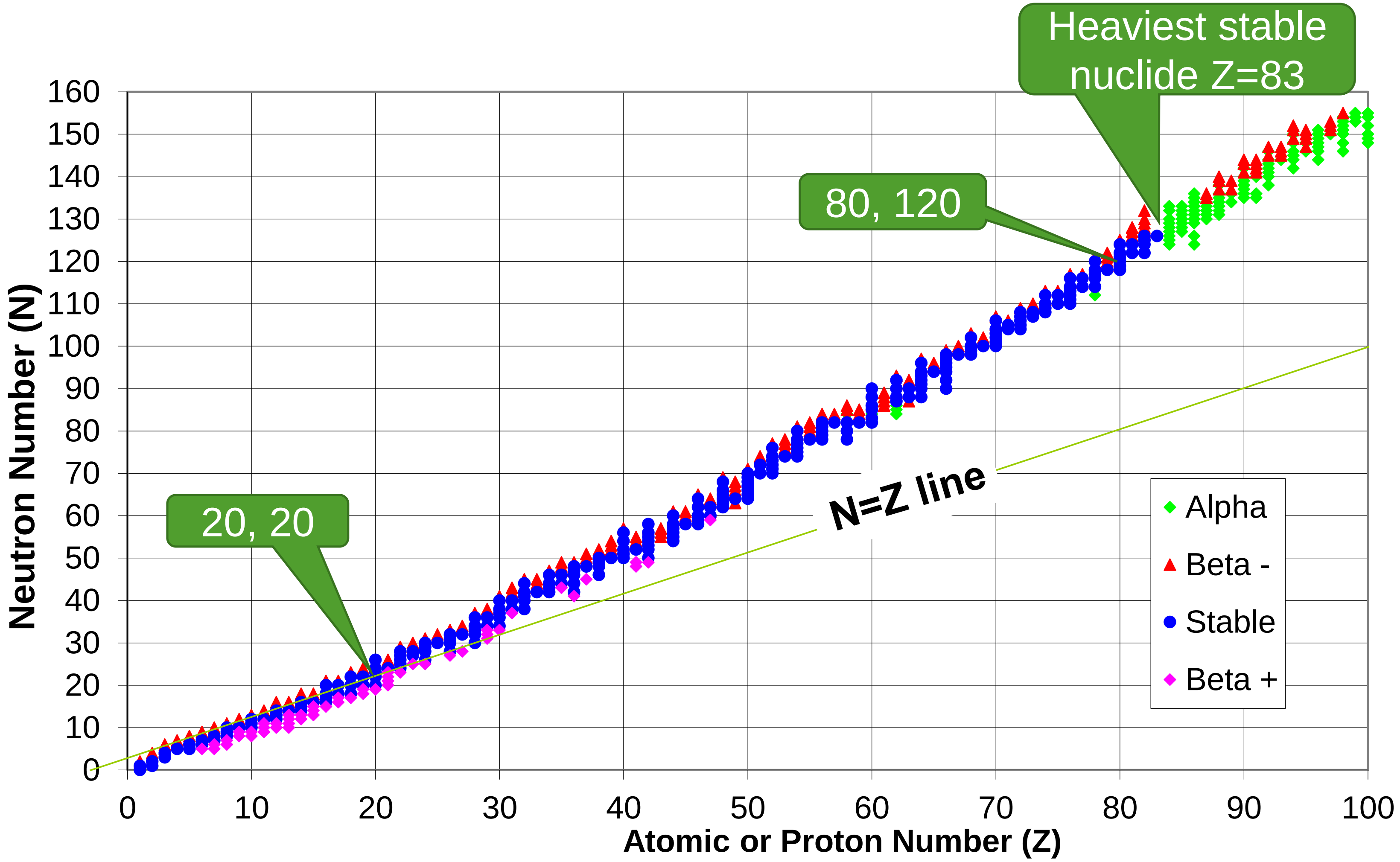


The nucleus has energy levels

After previous nuclear decay a nucleus will usually be in an excited state

When it transitions to the ground state, the energy is released as a gamma ray

Nuclides and instability



Stable nuclei with Z>20 have N>Z

Neutron-rich nuclei decay β^-

Proton rich nuclei decay β^+

Overlarge nuclei with good n/p balance decay α

Nuclear equation practice

Write the equations for the following decays

1. **Beta- decay of** ${}^{3}_{1}\mathrm{H}$ **to helium (He)**

2. **Alpha decay of** ${}^{238}_{92}\mathrm{U}$ **to thorium (Th)**

3. **Gamma decay of** ${}^{60}_{27}\mathrm{Co}$

Irradiation and Contamination

- Irradiation is when you receive ionizing radiation from a source. In general, this will not make you radioactive, and your dose will end once the source is not near you.
- Contamination is when a part of the source sticks to you, or is inhaled, consumed or otherwise becomes part of you. If this happens, you do become radioactive.

Background radiation

Radiation in the environment which is not related to the experiment we are doing. Dose is measured in sieverts (Sv)

Sources of background radiation (with typical annual doses) for a person in the UK include

- 1.3mSv - radon (radioactive gas coming up through rocks)
- 0.4mSv - rocks (especially igneous rocks like granite)
- 0.4mSv - medical uses of radioactivity
- 0.3mSv – food and drink
- 0.3mSv - the Sun, and cosmic radiation (from outside the solar system)
- 0.01mSv - fallout from the testing of nuclear weapons & nuclear accidents

Sources: Nuclear Industry Association and UK Radioactive Waste Inventory for fractions, gov.uk for totals.

Background correction

The number of decays each second is the activity.

Activity is measured in becquerel (Bq).

Example: Before an experiment is done, the background radiation gives 30 counts in 120s. During an experiment, 120 counts are measured in one minute

Activity, number and mass

Activity is proportional to the number of undecayed nuclei

$$A = \lambda N = \frac{\lambda M N_A}{M_r} = \frac{\lambda M}{m}$$

λ = decay constant (s^{-1}), and for all but the shortest half lives can be thought of as the probability that a given nucleus will decay in one second.

M = mass of sample, M_r = molar mass, N_A = 6.02x10^{23} mol^{-1},
m = atomic mass ≈ mass number x 1u   1u = 1.661x10^{-27}kg

Decay constant related to half life *T*:

$$\lambda = \frac{\ln 2}{T}$$

Activity example

Tritium (^3H) is used in emergency exit signs. The beta particles give energy to fluorescing atoms. Calculate the mass of tritium needed to emit 2000 beta particles each second. The half life of tritium is 12.3 years.

Activity practice

1. Calculate the number of nuclei needed to have an activity of 250Bq if the half life is 12.3 years.

2. Calculate the activity of 3g of ^{235}U (half life 2.22×10^{16}s)

3. Calculate the power output of 50g of ^{60}Co if each gamma has energy 1.3MeV, and the half life is 5.27 years (1.66×10^{8}s).

Uses of radiation

- Smoke alarm
  - alpha particles ionize air, enabling it to conduct electricity
  - smoke from a fire stops the current, triggering the alarm
- Medical diagnosis (investigation)
  - usually a small quantity of a gamma emitter is injected into the patient, attached to a suitable molecule
  - ideal half life is about 6 hours
  - special cameras can monitor where it goes in the body
- Medical therapy (treatment)
  - cancerous cells have higher metabolic rate than healthy ones
  - targeting beams of gamma rays kills them more easily (radiotherapy)

Half life

Radioactive decay is a random process

You can not predict when a nucleus will decay

With many billions of nuclei in a sample, you can predict when half of them will have decayed – the half life.

The average number of nuclei (and the activity) halves with each half life.

Start
120 Bq

12 years
60 Bq

24 years
30 Bq

36 years
15 Bq

Half life

An activity of 500Bq means that $\frac{dN}{dt} = -500$

It follows that

$$\frac{dN}{dt} = -A = -\lambda N \qquad \frac{dA}{dt} = -\lambda A$$

The solution is

$$N = N_0 e^{-\lambda t} \qquad A = A_0 e^{-\lambda t}$$

Some problems are easier to solve using

$$N = N_0 \left(\frac{1}{2}\right)^{t/T} \qquad A = A_0 \left(\frac{1}{2}\right)^{t/T}$$

$$N = N_0 e^{-\lambda t} = N_0 e^{-\lambda \ln 2/T} = N_0 \left(e^{-\ln 2}\right)^{t/T} = N_0 \left(\frac{1}{2}\right)^{t/T}$$

Calculating time

If time requires evaluation:

$$N = N_0 e^{-\lambda t}, \qquad \frac{N}{N_0} = e^{-\lambda t}, \qquad \ln\frac{N}{N_0} = -\lambda t$$

Example: calculate the time taken for the activity of a tritium light source (*T*=12.3 years) to drop to 70% of its initial level.

Half life practice

1. The half life of tritium ($^{3}_{1}H$) is 12 years. If the background corrected count is 360 counts/min today, what would you expect it to be in 7 years time?

2. The half life of $^{99}_{43}Tc$ is 6.0 hours. After what time does the activity fall to 20% if its initial level?

Inverse square law for gamma

Gamma rays are not appreciably absorbed by air over short distances.

If activity is A, then number passing through each unit area at a distance r from the source is

$$I = \frac{A}{4\pi r^2}$$

Note that Ir^2 is a constant for this source.

Example: a detector 30cm from a gamma source records 457 counts in 30s, with the background level being 12 counts in 60s. What total count rate would be expected 13cm from the source?

Inverse square law practice

1. How far away from a 3.2kBq gamma source would you have to be before the gamma intensity was <3.0Bq/cm^2?

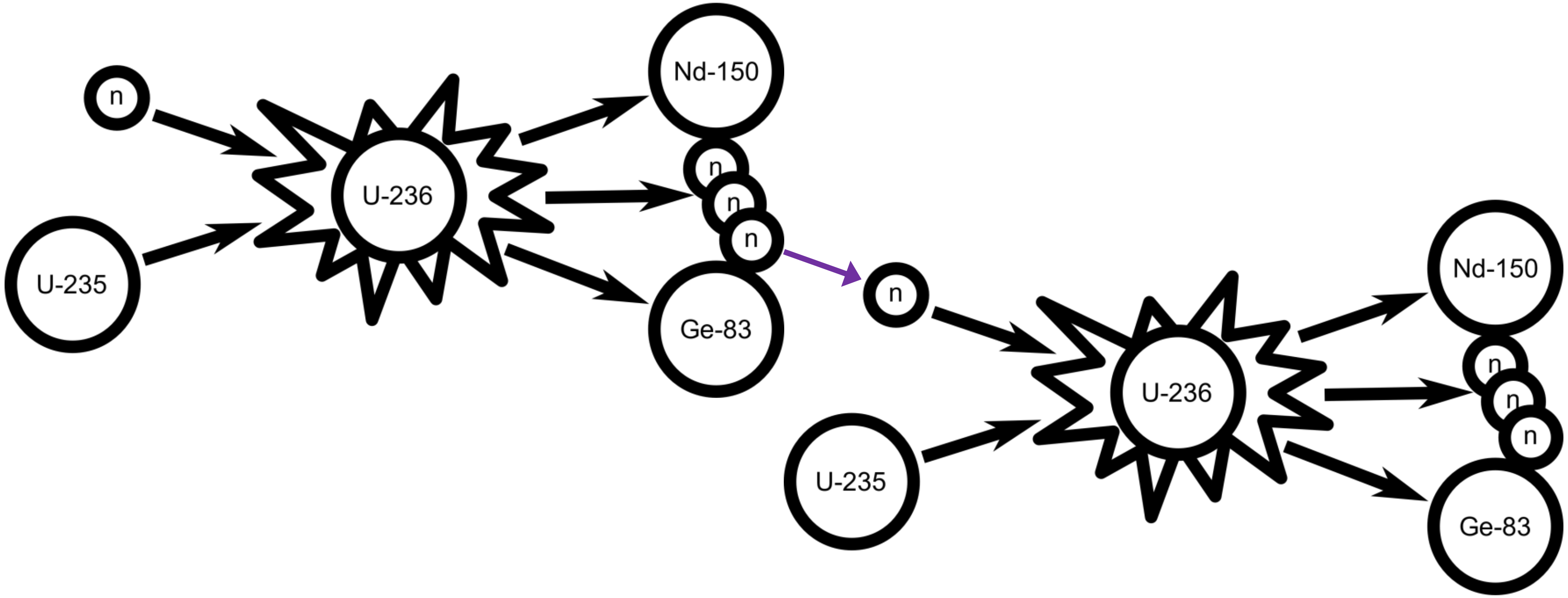
2. A detector counts 1.5% of the gamma rays passing it, has an effective area of 9cm^2, and is placed 15cm from a gamma source. After correction for background, it detects 260 counts per minute. What is the activity of the source?

Fission

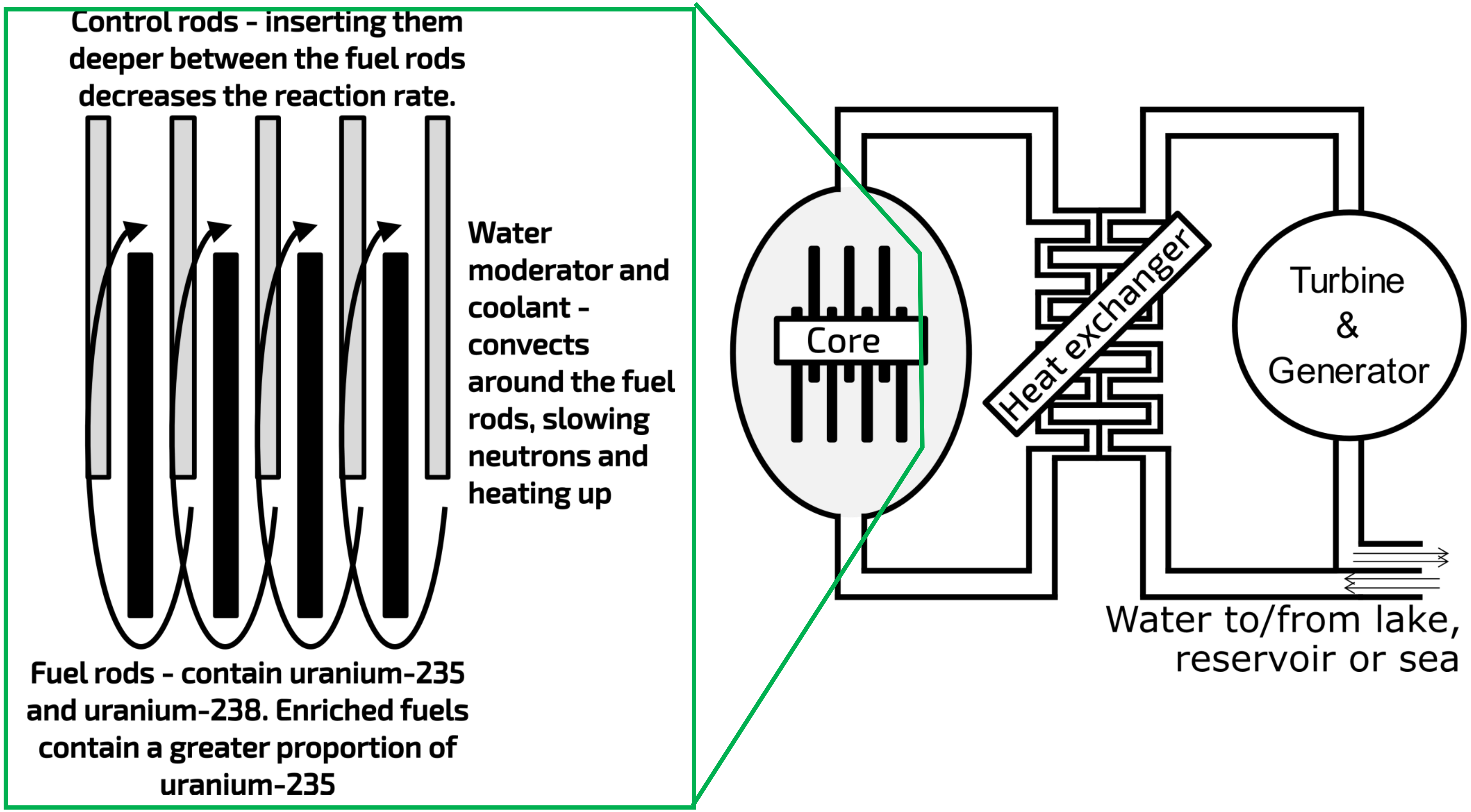
Some nuclei, such as uranium, split after absorbing a neutron

Neutrons are given out, which can trigger more reactions

All particles given out have high kinetic energy



Nuclear reactor



Nuclear Reactor

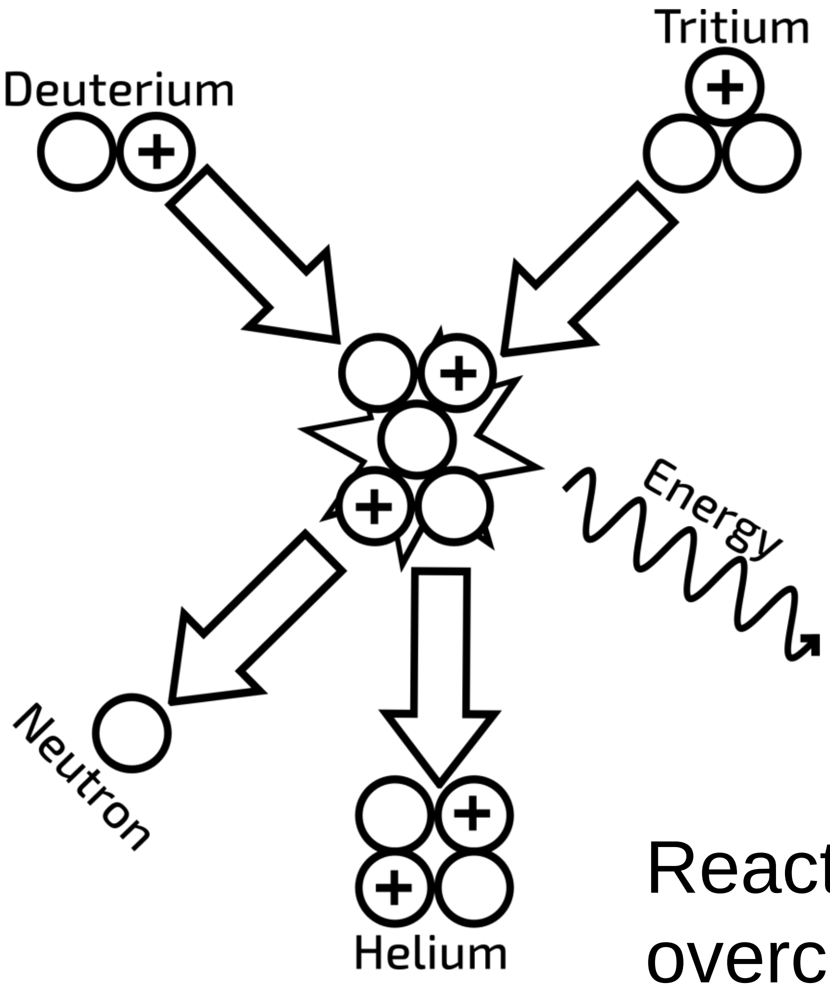
Moderator

- usually water (can be graphite)
- slows down neutrons
- to make further fission likely
- involves hundreds of elastic collisions for each neutron
- neutrons slow from MeV energies to approx. 300m/s (thermal energies)
- **required** for reactor to work

Control rods

- usually boron (can be cadmium)
- absorbs neutrons
- lowered into core to reduce reactivity
- raised into core to increase reactivity
- dropped into core in emergency

Fusion



Two small nuclei (hydrogen) join to make a larger nucleus

Particles come out with high kinetic energy

Once stationary, products have less mass than reactants

Reaction requires high temperatures to overcome repulsion of reactants

Energy release calculation

Mass and energy are equivalent

Total energy of products (released at high speed) from a nuclear reaction is equal to the total energy of the reactants (at rest). When the products slow down, the kinetic energy is lost to the surroundings.

Energy released = $(\text{Rest mass of reactants} - \text{rest mass of products})c^2$

Energy released (MeV) = Mass difference (u) x 931

Energy release example

Using the data, work out the energy release

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

Nuclide	Mass/10^{-27}kg
n	1.6749
^{2}H	3.3436
^{3}He	5.0064

$$ {}^{235}_{92}U + n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n $$

Nuclide	Mass/u
n	1.0087
^{235}U	235.0439
^{141}Ba	140.9239
^{92}Kr	91.9262

Energy release practice

Using the data, work out the energy release

$$^{1}_{1}H + ^{14}_{7}N \rightarrow ^{15}_{8}O$$

Nuclide	Mass/10^{-27}kg
^{1}H	1.6726
^{14}N	23.2463
^{15}O	24.9059

$$^{239}_{94}Pu + n \rightarrow ^{133}_{53}I + ^{105}_{41}Nb + 2n$$

Nuclide	Mass/u
n	1.0087
^{239}Pu	239.0522
^{133}I	132.9078
^{105}Nb	104.9239

Lighter than the sum of its parts

When protons and neutrons come together to form a nucleus, they attract by the strong nuclear force

The nuclear potential energy reduces under this attraction

This lowering of energy also lowers the mass

Mass difference = Mass of individual particles – Mass of nucleus

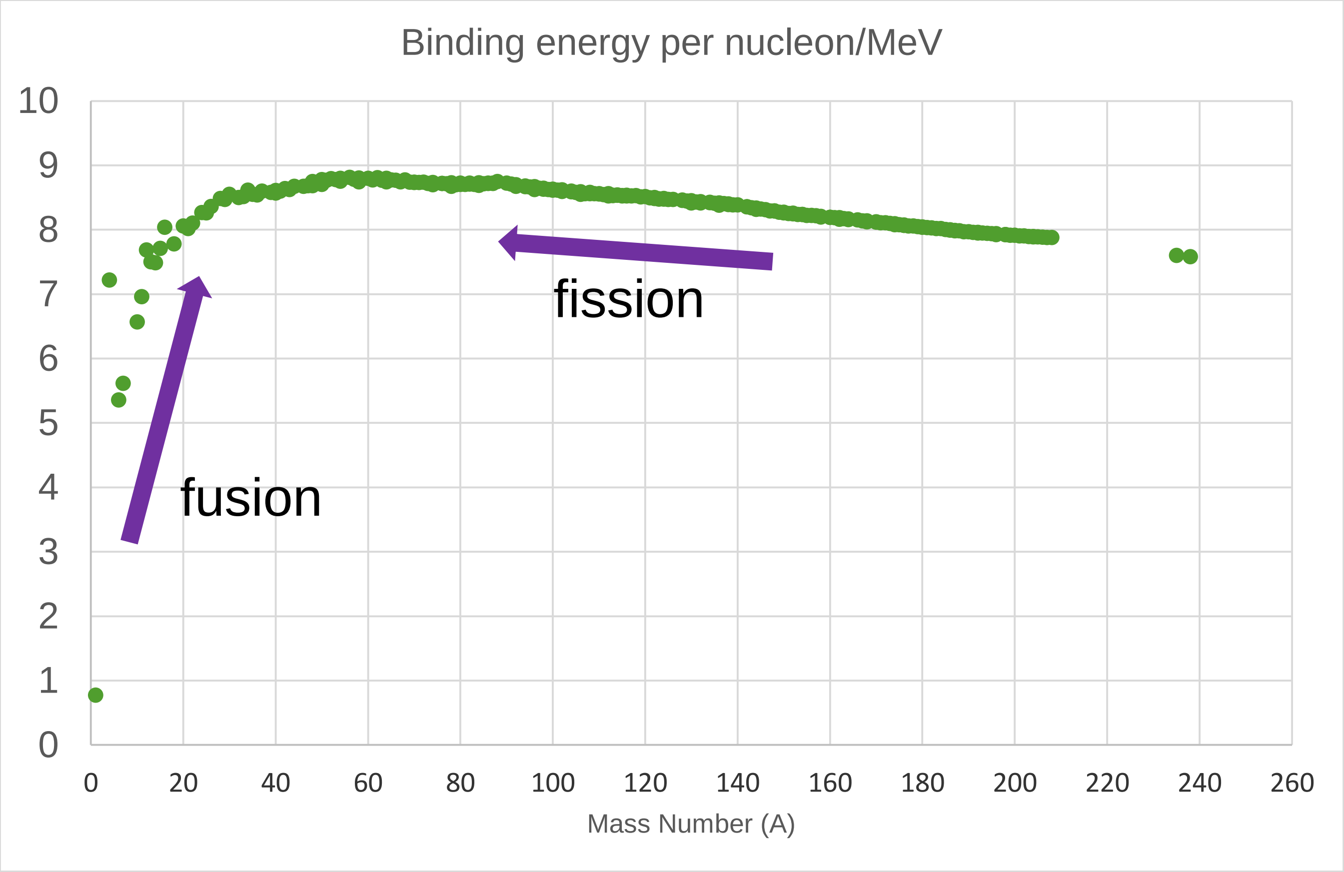
Binding energy (J) = Energy required to separate nucleons

= Mass difference (kg) x c^2

Binding energy (MeV) = Mass difference (u) x 931

Binding energy per nucleon (BE/A) = $\dfrac{\text{Binding energy}}{\text{mass number of nucleus}}$

Binding energy per nucleon



Energy can be released by climbing the curve

Joining small nuclei, or Splitting large ones

Binding energy example

Calculate the binding energy per nucleon

$$^{90}_{36}Kr$$

Nuclide	Atomic mass/u
e	0.0005
p	1.0072
n	1.0087
^{90}Kr	89.9195

Binding energy practice

Calculate the binding energy per nucleon

1. $^{105}_{41}Nb$

2. $^{133}_{53}I$

Nuclide	Atomic mass/u
e	0.0005
p	1.0072
n	1.0087
^{105}Nb	104.9239
^{133}I	132.9078

Energy release from B.E.

Energy release = total BE of products – BE of reactants

Loose nucleons have zero binding energy

Example: calculate energy release of:

$$^{3}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + n$$

Nuclide	BE/A (MeV)
^{3}H	2.8273
^{4}He	7.0739

Energy release from B.E. practice

Calculate the energy release in

1. $^{1}_{1}H + ^{14}_{7}N \rightarrow ^{15}_{8}O$

2. $^{12}_{6}C + ^{12}_{6}C \rightarrow ^{24}_{12}Mg$

Nuclide	BE/A (MeV)
^{12}C	7.6801
^{14}N	7.4756
^{15}O	7.4637
^{24}Mg	8.2607

Links

A Level Topic Revision

https://isaacphysics.org/pages/a_level_topic_index#a_level_revision

Consolidation Programme

https://isaacphysics.org/pages/summer_programmes_2021