Revision Guide for Chapter 18

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Student's Checklist

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I can show my understanding of effects, ideas and relationships by describing and explaining cases involving:

the nature and effects of ionising radiations (e.g. x-rays, gamma rays, beta particles and alpha particles): • differences in ionising and penetrating abilities • effects of the radiations on materials, especially living tissue • the doses obtained from different sources (e.g. background radiation, medical diagnosis and treatments, TV sets, nuclear power stations, etc) Revision Notes: Ionising radiation; Biological effects of ionising radiation; Risk Summary Diagrams: Doses from different sources	
the structure of a nucleus; stability and decay of nuclei in terms of binding energy Revision Notes: Nucleus; Nuclear stability; Binding energy Summary Diagrams The nuclear valley; Calculating binding energy	
the transformations of nuclei when they emit radiation (e.g. increase in proton number on emitting an electron; decrease of nucleon number and proton number on emitting an alpha particle; no changes on emission of a gamma ray) Revision Notes: Nuclear transformations Summary Diagrams: Radioactive decay processes; A decay chain	
nuclear fission and fusion; changes in binding energy Revision Notes: Fission; Fusion Summary Diagrams: Energy from nuclear fission; Chain reactions; Fusion reactions	

I can use the following words and phrases accurately when describing effects and observations:

nucleus: nucleon, proton, neutron, nucleon number, isotope Revision Notes: Nucleus;	
binding energy Revision Notes: Nuclear stability; Binding energy Summary Diagrams The nuclear valley; Calculating binding energy	
activity, probability, half-life, decay constant Revision Notes: Exponential decay	

nuclear fission, nuclear fusion Revision Notes: Fission; Fusion	
risk, absorbed dose in gray, equivalent dose in sievert Revision Notes: Biological effects of ionising radiation; Risk	

I can sketch and interpret:

plots of binding energy per nucleon versus proton number and neutron number Revision Notes: Nuclear stability; Binding energy Summary Diagrams The nuclear valley; Calculating binding energy	

I can make calculations and estimates making use of:

half-life, the decay constant and activity $\frac{dN}{dt} = -\lambda N$ $N = N_0 e^{-\lambda t}$ Revision Notes: Exponential decay	
the comparison of equivalent doses in sieverts Revision Notes: Biological effects of ionising radiation	
energy changes from nuclear transformations using the relationship $E_{rest} = mc^2$ Revision Notes: Binding energy Summary Diagrams Calculating binding energy	

Revision Notes

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Ionising radiation

Ionising radiation is any form of radiation capable of ionising neutral atoms or molecules. Types of ionising radiation include:

1. Alpha particles which each consist of helium nuclei (two protons and two neutrons) emitted from massive unstable nuclei.
2. Beta particles which consist of electrons or positrons emitted by nuclei that have an excess of neutrons or protons respectively.
3. Gamma radiation which consists of high-energy photons emitted by nuclei in excited states.
4. X-radiation which consists of high-energy photons emitted when fast-moving electrons are stopped in an x-ray tube.
5. Mesons from cosmic rays striking the atmosphere.

Alpha radiation

The alpha particles from any one type of decay all have the same energy, typically a few MeV. Being fast moving massive charged particles, alpha particles ionise strongly. The range of alpha radiation in air is of the order a few centimetres. In solid materials, alpha particles are stopped very easily, even by a thin sheet of paper. Thus the main danger to health from alpha radiation comes from ingesting or breathing in the radioactive material, when the alpha particles are stopped in body tissues, causing damage.

Beta radiation

Both electrons and positrons are known as beta particles, sometimes written β^- and β^+ respectively. In beta decay, neutrinos (or antineutrinos) are also emitted, and carry away energy and momentum. The energies of beta particles therefore vary, up to the maximum available from the decay, typically a few MeV.

Beta particles have a range of about a metre in air. They penetrate thin layers of solid material, for example aluminium foil, but are stopped by a few millimetres thickness of metal.

Gamma radiation

The gamma photon energies for a particular excited state form a line spectrum characteristic of that isotope. The photon energy is typically 100 keV to 1 MeV. X-rays have the same nature, and similar properties, though generally have smaller photon energies.

Gamma radiation has less ionising effect than alpha or beta particles of the same energy. Thus it passes through air with little absorption. The intensity of gamma radiation from a point source varies approximately as the inverse square of the distance from the source. Gamma photons are largely absorbed by lead plates of thickness about 50 mm.

The intensity I of a beam of gamma-ray photons is reduced by placing thick massive material in the path of the beam, in accordance with the equation $I = I_0 e^{-\mu x}$, where I_0 is the initial intensity of the beam, μ is the **absorption coefficient** of the material and x is its thickness. The unit of μ is m^{-1}.

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Biological effects of ionising radiation

Ionising radiation can be injurious to health, but is also used in many kinds of medical treatment and investigation. Intense gamma radiation is used to sterilize medical supplies and to preserve some foods.

Ionising radiation kills living cells as a result of damaging cell membranes beyond repair and destroying the mechanism of replication in cells as a result of damaging the DNA strands in cell nuclei. Ionising radiation also creates free radicals which affect cell chemistry.

The **absorbed dose** of ionising radiation received by a body is the amount of energy from that radiation absorbed per kilogram of the body. The SI unit of absorbed dose is the gray (Gy), equal to 1 J kg^{-1}. This is a very large unit, comparable to the lethal dose.

The **dose equivalent** is the dose of 250 kV x-rays needed to give the same biological effect as the ionising radiation. The SI unit of dose equivalent is the sievert (Sv) which is equal to 1 J kg^{-1} of 250 kV x-rays. The dose equivalent can be calculated by multiplying the absorbed dose in gray by a quality factor for the type of radiation involved:

Dose equivalent = radiation dose $\times$ quality factor.

Radiation	Quality factor	Dose equivalent of 1 gray
alpha	20	20 sievert
beta	1	1 sievert
gamma and x-ray	1	1 sievert
neutron	10	10 sievert

There is no known lower limit for biological damage by ionising radiation. Maximum permissible dose limits are determined by law, in accordance with what is considered at the time to be acceptable in terms of risk. The maximum permissible dose equivalent in the UK for the general public is 0.5 mSv per annum above naturally occurring ionising radiation levels, and is 15 mSv per annum for occupations where ionising radiation is used. The average occupational dose is about 2 mSv per annum.

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Risk

The concept of risk combines the probability of an event for those exposed to its possibility, with the scale of the damage it would cause. Thus road traffic accidents are more frequent than air accidents, per mile or hour travelled, but air accidents kill more people per event. When the two factors are combined, air travel is the less risky.

There is no known lower limit of exposure for biological damage by ionising radiation. Radiation exposure limits are set by law, based on dose limits above which the risk of damage to human health is deemed unacceptable.

Current occupational radiation limits are based on an estimated death rate of about 50 per million persons per millisievert of dose equivalent. The current average dose received by the general public, much of it from background radiation including cosmic rays, is around 1 millisievert per year. Radiation safety limits attempt to ensure that risks due to radiation are no more significant than risks due to everyday activities.

See Summary Diagrams: Doses from different sources

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Nucleus

Every atom contains a nucleus which is composed of protons and neutrons. Because neutrons and protons are similar in many respects they are collectively termed nucleons. The nucleon number (also called the mass number) A of an isotope is the number of protons and neutrons in each nucleus of the isotope.

The particles in the nucleus are held together by the strong nuclear force. The nucleus of an isotope which has a proton number Z and a nucleon (mass) number A consists of Z protons and $N = A - Z$ neutrons. The symbol for an isotope is ${}^{A}_{Z}X$, where X is the chemical symbol of the element.

The proton number Z is also equal to the number of electrons in the atom, because a neutral atom must have the same number of negative electrons as positive protons. The number of electrons decides the chemical behaviour of the atom. It is therefore possible to have atoms with identical chemical behaviour, but with different mass, because their nuclei contain the same number of protons but different numbers of neutrons. They are called **isotopes**. For example, deuterium is an isotope of hydrogen. Both atoms have one electron, and both nuclei have one proton. But the deuterium nucleus has an extra neutron, increasing the mass of the atom without changing its chemical properties. Thus, just like hydrogen, deuterium combines with oxygen, forming 'heavy water'.

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Nuclear stability

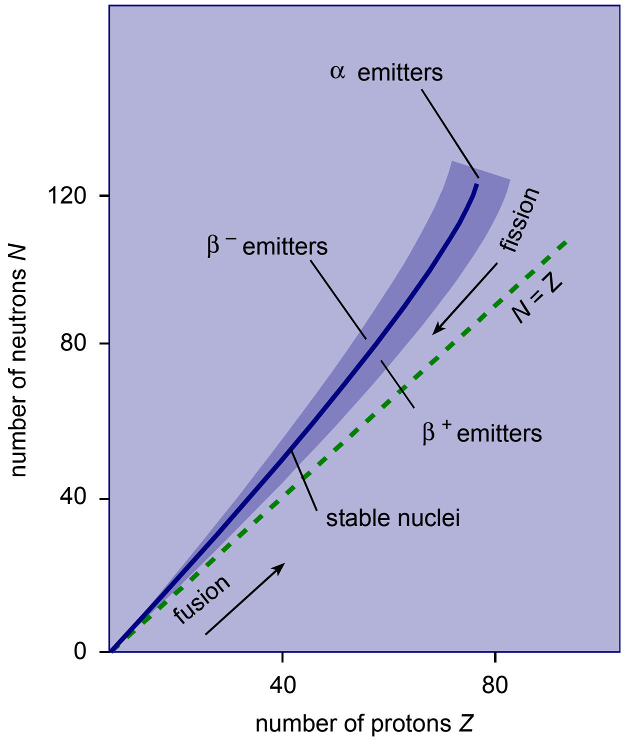
A particular combination of neutrons and protons can form a stable nucleus if the energy of the combination is less than the energy the particles would have if the nucleus were taken apart.

Thus a plot of neutron number N against proton number Z for nuclei which exist can be thought of as tracing the shape of an 'energy valley' (the binding energy) in the 'space' of possible proton and neutron numbers. The graph of neutron number N against proton number Z for all the known nuclei shows key features of nuclear stability:

1. Light stable nuclei lie along a narrow belt with $N / Z \approx 1$; more massive stable nuclei show a trend towards more neutrons than protons.
2. The graph of stable nuclei is 'fringed' on either side by the presence of unstable isotopes, which decay by going 'downhill' towards the line of greatest stability. Neutron-rich isotopes emit electrons, increasing the proton number. Proton-rich nuclei emit positrons, increasing the neutron number.
3. Very massive nuclei decay in the direction of becoming less massive, either emitting alpha particles or by spontaneous nuclear fission, breaking into two less massive nuclei.
4. Very light nuclei can fuse to make more massive nuclei.

The 'deepest' part of the 'energy valley' is near iron, $Z = 26$, the most stable region. The 'side walls' of the 'energy valley' are steep, because the departures of N and Z from the stable line are never large.

The N - Z plot



See Summary Diagram: The nuclear valley

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Binding energy

The binding energy of a nucleus is the amount by which the rest energy of a nucleus is less than the rest energy of its constituent neutrons and protons.

Binding energy is often expressed in millions of electron volts (MeV)

The protons and neutrons in a nucleus are bound by the strong nuclear force, which is a short-range attractive force sufficient to overcome the electrostatic force of repulsion between the protons in a nucleus. As a result, the rest energy of the nucleus is less than that of its constituent particles. Since the rest energy E_{rest} is related to the mass m by the relation $E_{rest} = mc^2$, the mass of the nucleus is also less than that of its constituent particles.

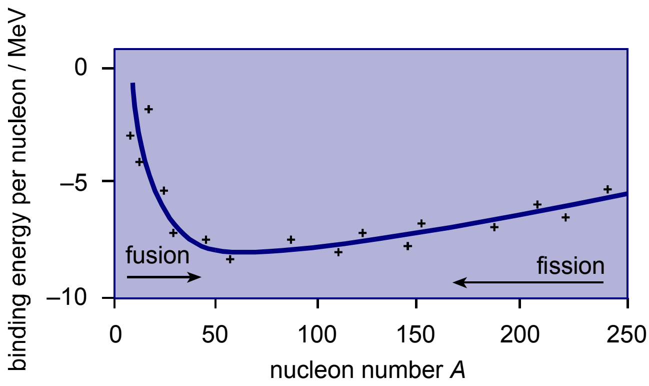
The binding energy of a nucleus can be calculated from the difference in mass between the nucleus and its separate neutrons and protons. For a nucleus with Z protons and N neutrons, mass defect Δm = mass of nucleus – ($Z\,m_p + N\,m_n$). The binding energy = Δmc^2.

The mass of a nucleus is usually given in atomic mass units (1 u).
1 u = 1.66×10^{-27} kg.

The rest energy corresponding to 1 u = 1.66×10^{-27} kg $\times$ (3.00×10^{8} m s^{-1})^2 = 1.49×10^{-10} J = 933 MeV / u.

Binding energy in MeV = mass defect in atomic mass units $\times$ 933 MeV / u.

The binding energy curve



The graph shows how the binding energy per nucleon varies with the nucleon number *A*. The graph can be thought of as the depth of the 'nuclear valley' along the line of stable nuclei mapped on a plot of neutron number *N* against proton number *Z*.

Key features of the curve of binding energy per nucleon are:

1. The most stable nuclei occur at about *A* = 50 where the binding energy is about –8.5 MeV per nucleon. For this reason the end product of nuclear reactions in stars as they evolve is elements close to iron.
2. Light nuclei fusing together to form heavier nuclei release energy as the binding energy per nucleon becomes more negative.
3. Heavy nuclei can release energy as a result of fission. The energy released per fission is the difference between the binding energy of the fragment nuclei and the initial nucleus.

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Nuclear transformations

A radioactive isotope decays as a result of one of the following **nuclear transformations**:

Alpha emission, in which the unstable nucleus emits two protons and two neutrons as a single particle

$${}^{A}_{Z}X \rightarrow {}^{4}_{2}\alpha + {}^{A-4}_{Z-2}Y.$$

Electron emission, together with an antineutrino, in which a neutron in the nucleus changes into a proton:

$${}^{A}_{Z}X \rightarrow {}^{0}_{-1}\beta + {}^{A}_{Z+1}Y + \bar{\nu}$$

Positron emission, together with a neutrino, in which a proton in the nucleus changes into a neutron:

$${}^{A}_{Z}X \rightarrow {}^{0}_{+1}\beta + {}^{A}_{Z-1}Y + \nu$$

Gamma emission, in which a gamma-ray photon is emitted from a nucleus in an excited state, which changes to a state of lower energy, without change of proton or neutron number.

A radioactive isotope may produce a daughter isotope which itself is radioactive. There are several naturally occurring series of such radioactive decay series of such nuclear transformations. Each series consists of a sequence of alpha and beta emissions, each emission with a characteristic half-life giving rise to a daughter isotope. Gamma radiation is emitted after the majority of such decays.

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Fission

Nuclear fission is the splitting of a nucleus into two fragments with the release of energy. Neutrons released in this process may go on to induce further fission in other nuclei. Uranium-235 is the only naturally occurring fissile isotope.

A large nucleus may be considered like an oscillating liquid drop. If the nucleus oscillates too much, it can divide into two parts which repel each other electrostatically. The two fragments gain kinetic energy and also release two or three high-energy neutrons. In a nuclear reactor, these neutrons can go on to produce further fission, controlled so that on average exactly one fission neutron per fission causes a further fission. The other fission neutrons are absorbed by other nuclei or escape from the reactor. Thus a **chain reaction** is established in which fission occurs at a steady rate.

See Summary Diagrams: Chain reactions

The binding energy per nucleon becomes more negative by about 1 MeV as a result of the fission, giving a total energy release of the order of 200 MeV from the fission of a nucleus with about 200 nucleons.

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Fusion

Light nuclei release energy when they are fused together. This is because the additional nucleons bind the larger nucleus together more strongly.

To make two nuclei fuse together, the nuclei must approach each other to within a distance of about 10^{-15} m, which is the range of the strong nuclear force. This is achieved inside a star as a result of its high core temperature. Fusion is, however, extremely rare, notably because a proton must convert to a neutron during the short collision time. This is why stars have very long lifetimes.

The fusion reaction in stars releases about 28 MeV per helium nucleus formed, which is about 7 MeV per nucleon.

Fusion reactors attempt controlled fusion in a plasma of ionised hydrogen contained by magnetic fields. The plasma is heated by passing a very large electric current through it. The fusion process releases a total of 22.8 MeV for every four protons and neutrons fused into a helium nucleus. However, at present fusion in such a reactor cannot produce more power than is supplied to it for any appreciable length of time.

See Summary Diagrams: Fusion reactions

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Exponential decay

Radioactive decay is a random process. All nuclei of a radioactive isotope are equally likely to decay, thus the number of nuclei ΔN that decay in a given time Δt is proportional to the number N of nuclei of the isotope present at that time. Hence $\Delta N = -\lambda N \Delta t$, where λ is the **decay constant**. Note that the minus sign indicates a decrease of N with time.

The rate of decay, or **activity**, is:

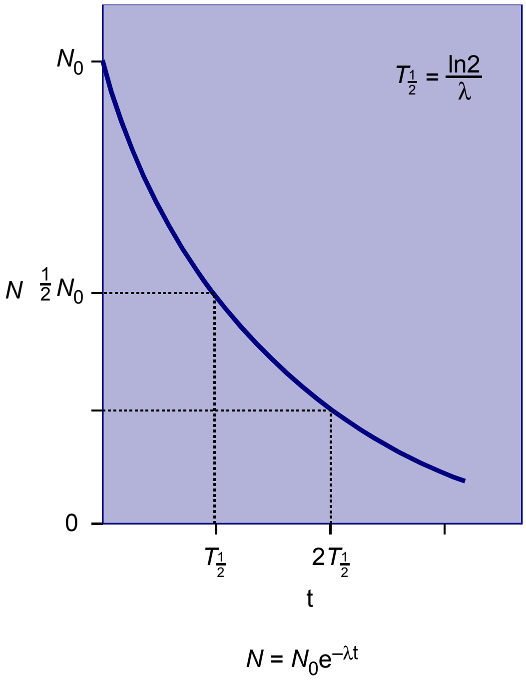
$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N.$$

The solution of this equation is

$N = N_0 e^{-\lambda t}$
where N_0 is the initial number of nuclei at $t = 0$.

After one half-life $t_{1/2}$, $N = 0.5\ N_0$. Thus:
$0.5N_0 = N_0 e^{-\lambda t_{1/2}}$
whence $\lambda\ t_{1/2} = \ln 2$.

The graph shows how N decreases with time. This type of curve is called an exponential decay curve.



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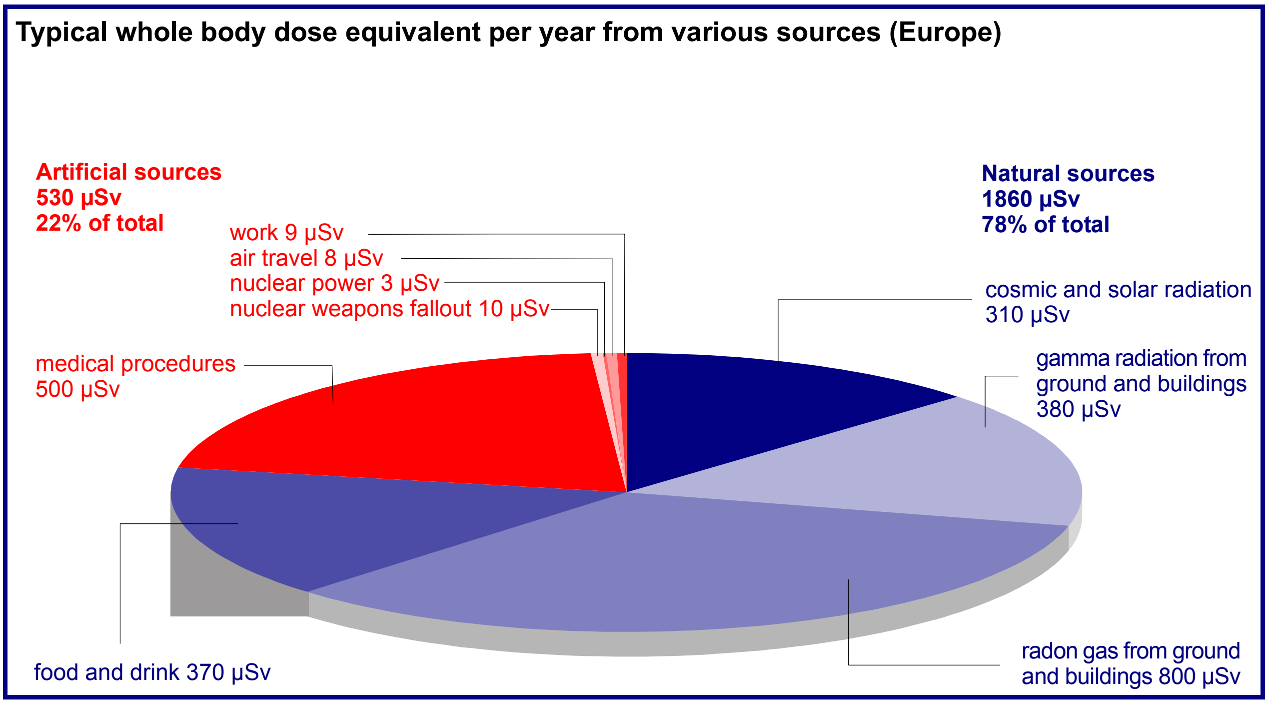
Doses from different sources



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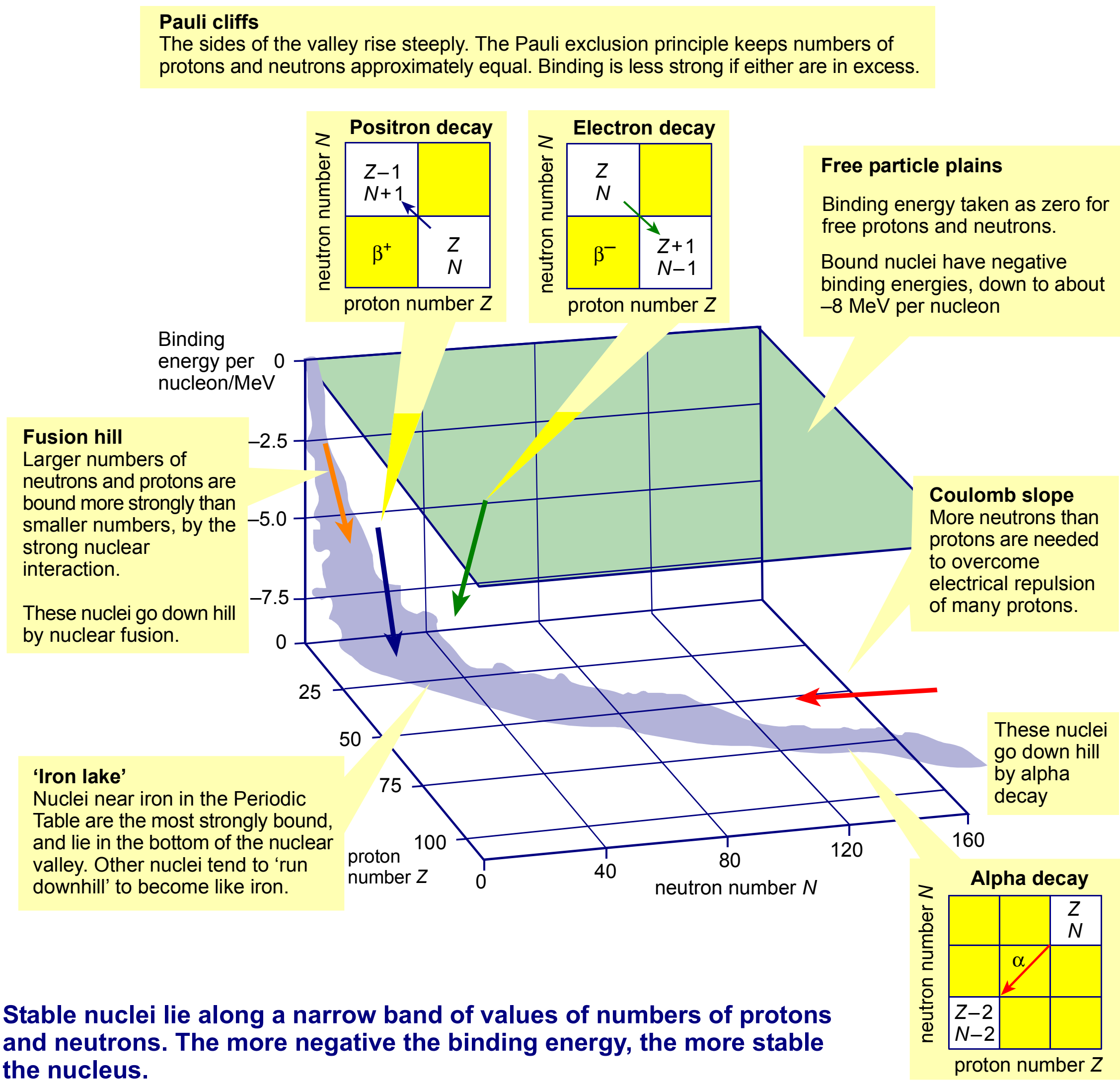
The nuclear valley

Nuclear landscape: The nuclear valley of stability



Stable nuclei lie along a narrow band of values of numbers of protons and neutrons. The more negative the binding energy, the more stable the nucleus.

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Calculating binding energy

Binding energy of carbon-12 nucleus

Mass of carbon-12 atom

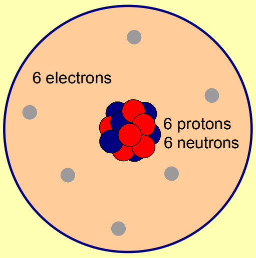
1 atomic mass unit u
= 1/12 of mass of C-12 atom
1 u = 1.66056 × 10^{-27} kg

mass of C-12 atom = 12.0 u

Mass of 6 electrons

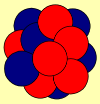
mass of electron
= 9.1095 × 10^{-31} kg
= 0.000549 u

mass of 6 electrons = 0.0033 u



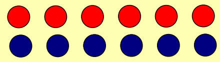
Calculate mass of carbon-12 nucleus

mass of carbon-12 nucleus
= mass of carbon-12 atom
– mass of 6 electrons



mass of carbon-12 nucleus
= (12.000 – 0.0033) u
= 11.9967 u

Calculate mass of all the protons and neutrons



mass of proton
= 1.67265 × 10^{-27} kg
= 1.00728 u

mass of neutron
= 1.67495 × 10^{-27} kg
= 1.00866 u

mass of 6 protons and 6 neutrons
= 6 (1.00728 + 1.00866) u
= 12.0956 u

Difference in mass

= mass of carbon-12 nucleus – mass of protons and neutrons
= (11.9967 – 12.0956) u
= – 0.0989 u

Binding energy

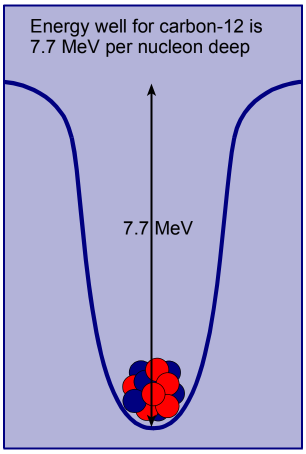
$E_{rest} = mc^2$

in mass units:
= – 0.0989 u
= – 1.643 × 10^{-28} kg

in energy units:
= – 1.477 × 10^{-11} J
= – 92.16 MeV

Binding energy per nucleon

–92.16 MeV for 12 nucleons
= – 7.7 MeV per nucleon



Binding energy of a nucleus is the difference between its mass and the sum of the masses of its neutrons and protons

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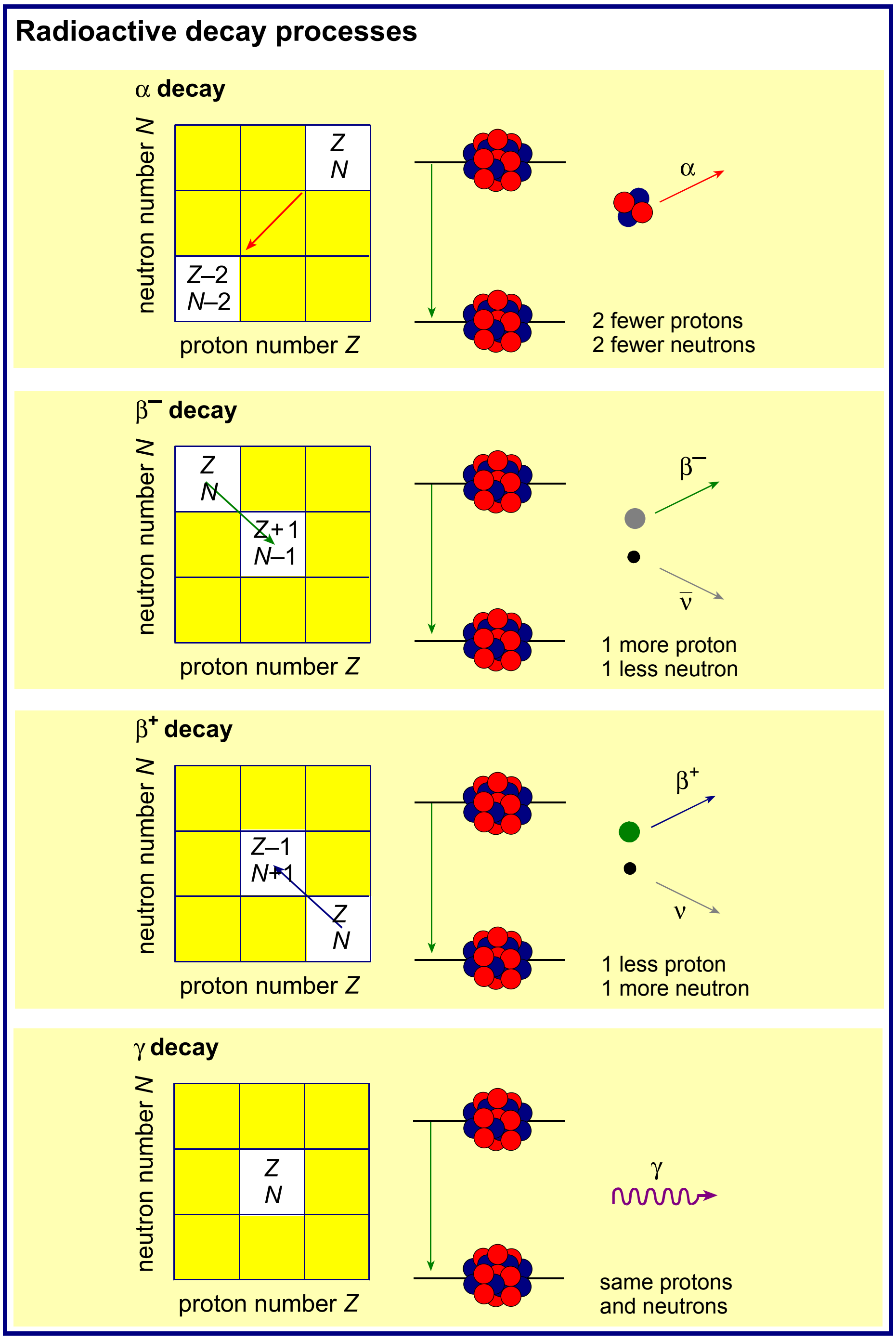
Radioactive decay processes



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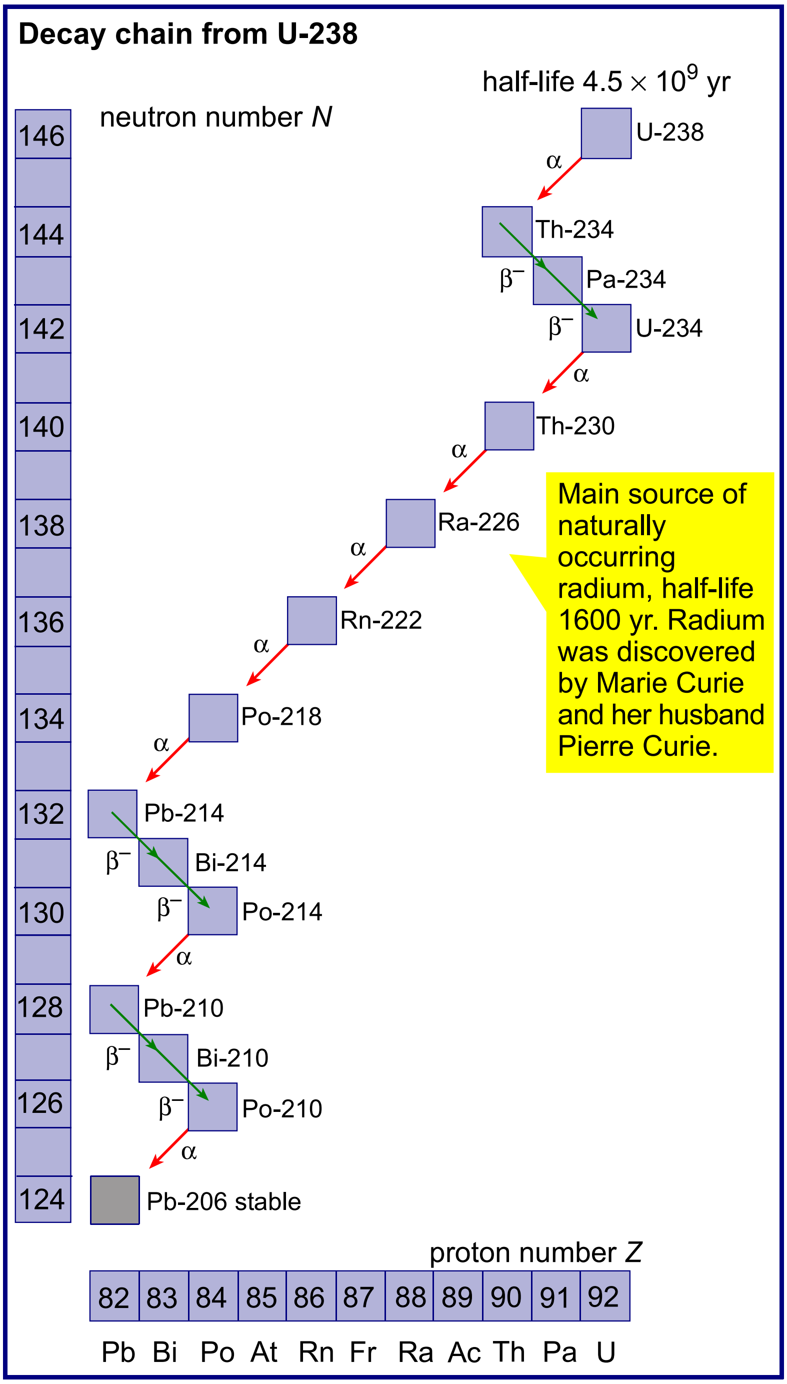
A decay chain



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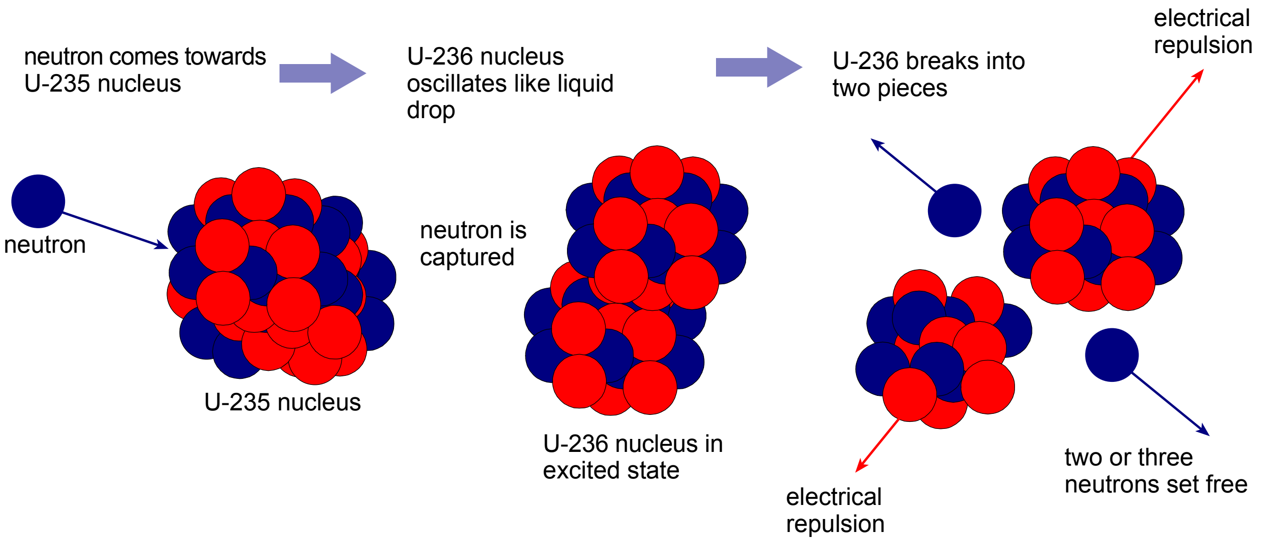
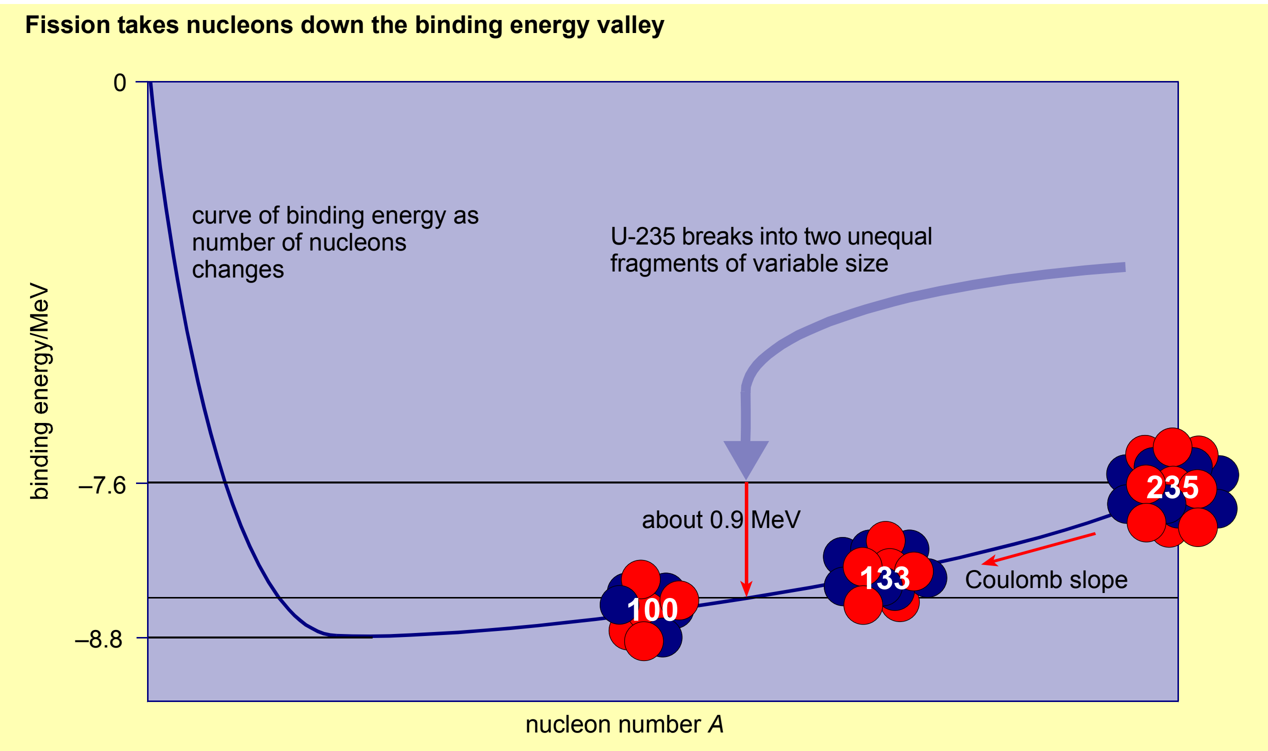
Energy from nuclear fission

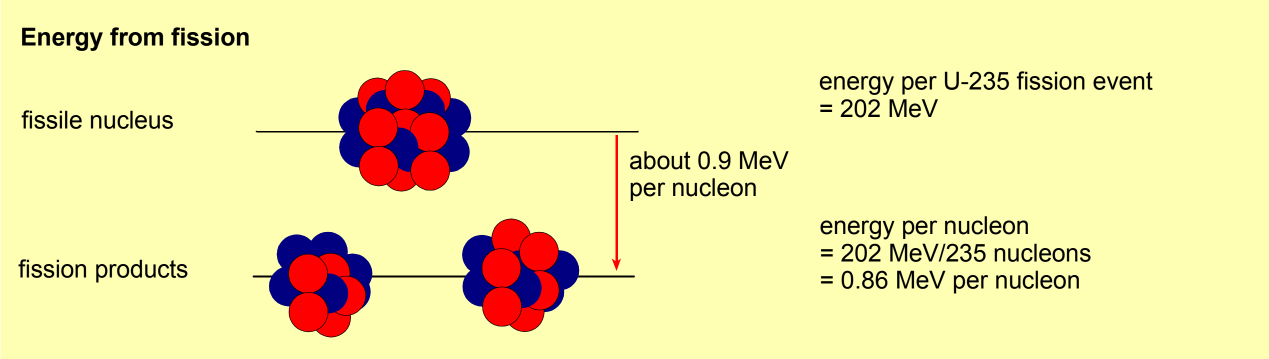
Nuclear fission of uranium-235



Nuclear fission of uranium-235



Nuclear fission of uranium-235



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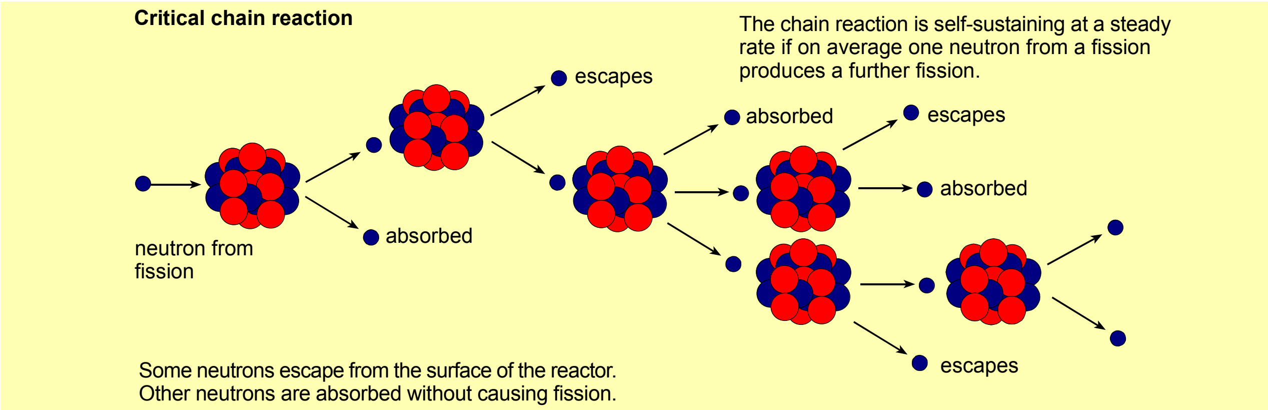
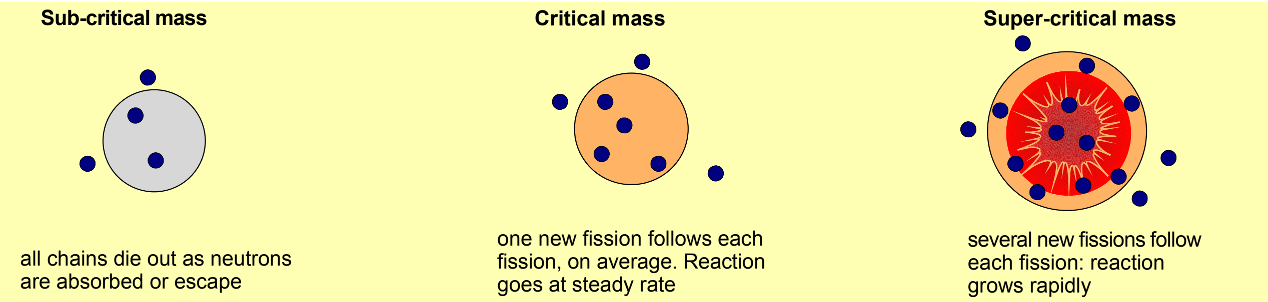
Chain reactions

Chain reaction and critical mass





Rate of escape of neutrons ∝ surface area
Rate of production of neutrons ∝ volume

ratio $\dfrac{\text{volume}}{\text{surface area}}$ increases with size

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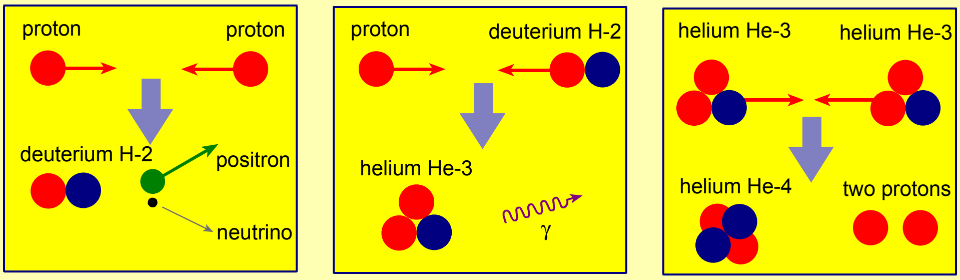
Fusion reactions

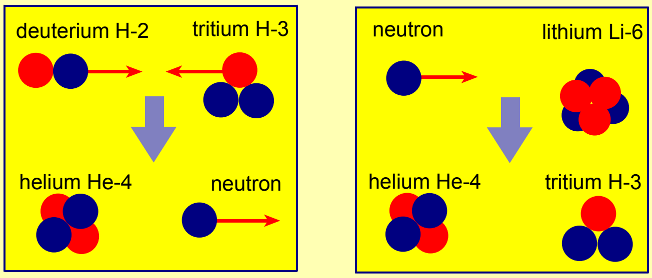
Fusion in the Sun and on Earth

Fusion in the Sun: three-stage process



Two protons fuse, converting one to a neutron, to form deuterium H-2. The deuterium H-2 captures another proton, to form He-3. Two He-3 nuclei fuse, giving He-4 and freeing two protons.

Fusion on Earth: two-stage process



Deuterium and tritium are heated to very high temperature. Neutrons from their fusion then fuse with lithium in a 'blanket' around the hot gases. Tritium is renewed.

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