Atomic Structure

The current model of atomic structure was not understood until the 20th century.

- 1808 - John Dalton – new idea - the matter is made of atoms (tiny indivisible spheres)
- 1897 - J. J. Thomson discovered that all matter contains tiny negatively-charged particles.
- He showed that these particles are smaller than an atom.
- He had found the first subatomic particle - the electron.

Thomson’s “plum-pudding” model

- Scientists then set out to find the structure of the atom.
- Thomson thought that the atom was a positive sphere of matter and the negative electrons were embedded in it.
- Ernest Rutherford got his students Geiger and Marsden to fire the fast moving α-particles at very thin gold foil and observe how they were scattered.

- 2 protons + 2 neutrons bound together into a particle identical to a helium nucleus; hence, it can be written as \(^{\alpha}He\) or \(^{\alpha}\alpha\)
- Rutherford source of \(\alpha\): radioactive radon

Rutherford’s conclusion (1911):

- \(\alpha\) particle had a head-on collision with a heavier particle
- heavier particle had to be very small, since very few \(\alpha\) particles were bounced back.
- heavy particles must be positive (repulsion)

→ nuclear (planetary) model of the atom:

Atom contains a small but very massive positive core which he called nucleus, surrounded by negatively charged electrons at relatively large distances from it.

The most surprising thing about this model is that the atom is mainly empty space!

which is why most \(\alpha\) particles went straight through – any electrons would hardly impede the relatively massive high speed \(\alpha\).

Using this model Rutherford calculated that the diameter of the gold nucleus could not be larger than 10^{-14} m.

Calculate the distance of an alpha particle’s closest approach to a gold nucleus.

\[
\alpha \text{ particle (}+2e\text{)} \quad \text{Gold nucleus (}+79e\text{)}
\]

Loss in kinetic energy must be equal to gain in potential energy of \(\alpha\) particle in the field of gold nucleus. Rutherford used an a source given to him by Madame Curie.

\[\text{The initial a energy was } = 7.7 \text{MeV} \quad (KE_{\text{initial}} = 7.7 \times 10^{-19} J \times 1.6 \times 10^{-19} \text{J} = 12 \times 10^{-31} \text{J}).\]

\(\alpha\) particle is brought momentarily to rest (‘having climbed as far as it can up the electrostatic hill’) when changing direction of the motion. The speed and hence the kinetic energy is zero, all the energy is now electrostatic potential energy.

\[KE_{\text{outside}} = U_{\text{inside}} = qV = (2e)\frac{Q_{\text{outside}}}{r} \quad r \approx 3 \times 10^{-14} \text{ m}\]

Radius of gold atoms is \(\approx 3 \times 10^{-10} \text{ m}.\) So a nucleus is at least 10 000 times smaller than an atom. It is important to emphasise that this calculation gives an upper limit on the size of the gold nucleus; we cannot say that the alpha particle touches the nucleus; a more energetic \(\alpha\) might get closer still.
Nuclear Atom

- No neutrons (AD 1911)

Orbiting around nucleus in circles are the electrons.

(If they were not orbiting but at rest, they would move straight to the nucleus; instead centripetal force is provided by the electrostatic attraction between electrons and nucleus.)

Problems with Rutherford’s model:

- According to Maxwell, any accelerating charge will generate an EM wave.
- Electrons will radiate, slow down and eventually spiral in to nucleus.
- The end of the world as we know it.
- The solution was found in quantum theory.

Bohr’s Model - atomic energy levels

- Electrons could only exist in certain orbits ("discrete states"),
- called "stationary states."
- Electrons in these stationary states do not emit EM waves as they orbit.
- Photon is emitted when an electron jumps from an excited state to a lower energy state.

Bohr’s model was so successful that he immediately received worldwide fame. Unfortunately, Bohr’s model worked only for hydrogen. Thus the final atomic model was yet to be developed.

The modern model

The model we now accept is that there is a nucleus at the centre of the atom and the electrons do exist in certain energy levels, but they don’t simply orbit the nucleus. The probability of finding electron somewhere is given by wave equations, resulting in some interesting patterns.

The result of this theory can be again visualised using very simple model, this time only energy level model. This model is not a picture of the atom but just represents possible energy of electrons.

For each element (atom/ion) produces a specific set of absorption (and emission) lines. We call this the "spectral signature" or "fingerprints" of an atom/ion.

- Allows the identification of elements across the galaxy and universe.
- (If we mapped it and can recognize it)
**Nuclear structure**

- **Nucleon**
The name given to the particles of the nucleus.

- **Nuclide**
A particular combination of protons and neutrons that form a nucleus. It is used to distinguish isotopes among nuclei.

- **Nucleon number (mass number) A**
The number of protons plus neutrons in the nucleus.

- **Proton number Z**
The number of protons in the nucleus.

- **Symbol for a nucleid**
\[ ^{\text{A} \, \text{Z}} \text{X} \]

- **Isotopes**
Nuclei (atoms) with the same number of protons but different numbers of neutrons.

- **Neutron number N**
The number of neutrons in the nucleus.

- **Isotopes – Nuclei (atoms) of the same element differing in masses due to different numbers of neutrons (the same proton number, different nucleon number).**

  - The existence of isotopes is evidence for the existence of neutrons, because there is no other way to explain the mass difference of two isotopes of the same element.
  
  - The same number of electrons – the same bonding - the same chemical properties
  
  - Different masses – different physical properties
  
  - Many isotopes do not occur naturally, and the most massive isotope found in nature is uranium isotope \[ _{92}^{238} \text{U} \]
  
  - About 339 nuclides occur naturally on Earth, of which 269 (about 79%) are stable
  
  - the current largest atomic number element, with atomic number 118, survived for less than a thousandth of a second

**The strong nuclear force**

- It is the force which attracts protons to protons, neutrons to neutrons, and protons and neutrons to each other. That force has a very short range, about 1.5 radii of a proton or neutron (1.5 x 10^{-14} m) and is independent of charge and this is the reason the nucleus of an atom turns out to be so small.

- If the protons can't get that close, the strong force is too weak to make them stick together, and competing electromagnetic force can influence the particles to move apart.

- As long as the attractive nuclear forces between all nucleons win over the repulsive Coulomb forces between the protons the nucleus is stable. It happens as long as the number of protons is not too high. Atomic nuclei are stable subject to the condition that they contain an adequate number of neutrons, in order to "dilute" the concentration of positive charges brought about by the protons.

- The most massive isotope found in nature is uranium isotope \[ _{92}^{238} \text{U} \]

  - For more massive nuclei strong nuclear force can't overcome electric repulsion.

**What holds the nucleus together?**

Protons are positive, neutrons are neutral (they would drift apart if put them together), so if the electric force was the only force involved, you couldn't create a nucleus.

There has to be some other force that holds protons and neutrons together and it must be stronger than the electric force. Well, in a brilliant stroke of imagination, physicists have named this force "the strong force."

Although the nuclear force is strong, nuclei do not attract each other, so that force must be very short range, unlike the electric force that extends forever.

The strong nuclear force was first described by the Japanese physicist Hideki Yukawa in 1935. It is the strongest force in the universe, 1038 times stronger than gravitational force and 100 times stronger than the electromagnetic force.
When nucleons bind together to form nucleus the mass of a nucleus is found to be less than the sum of the masses of the constituent protons and neutrons.

- **Mass defect (deficit)** - difference between the mass of a nucleus and the sum of the masses of its isolated nucleons.

A bound system has a lower potential energy than its constituent parts; this is what keeps the system together. The “mass defect” is therefore mass that transforms to energy according to Einstein’s equation and is released in forming the nucleus from its component particles.

- **Binding energy (BE)** - is therefore either the energy required to separate the nucleus into its individual nucleons or the energy that would be released in assembling a nucleus from its individual nucleons.

Calculations of binding energy

**Unified Atomic Mass Unit (amu abbreviated as u)**

1 u = $1.66053868 \times 10^{-27}$ kg

First find mass defect: $\delta = Z m_p + N m_n - M_{\text{nucleus}}$ in unified atomic mass units (u)

1 u is converted into $4.92 \times 10^{-10}$ J energy = 931.5 MeV:

$E = (1.66053868 \times 10^{-27} \text{ kg})(2.99792458 \times 10^8 \text{ m/s})^2 = 1.492417892 \times 10^{-10} \text{ J}$

1 electron volt = $1.60217646 \times 10^{-19}$ joules

$1.492417892 \times 10^{-10} \text{ J} = 1.60217646 \times 10^{-19} \text{ J} \times 931.5 \text{ MeV}$

**Binding energy**: mass deficit converted into energy $\Delta E = \delta c^2$

1 u of mass converts into 931.5 MeV → $\Delta E = \delta (u) \times 931.5 (\text{MeV})$

If a nucleus has a large binding energy then it will require a lot of work to pull it apart — we say it is stable.

The binding energy curve

**Graph of binding energy per nucleon**

BE varies with mass number:

BE increase as the mass (nucleon) number increases up to Fe.

Fe is most stable. After that it slightly decreases.

In most cases it is about 8 MeV/nucleon.
In 1896, Henri Becquerel discovered, almost by accident, that uranium can blacken a photographic plate, even in the dark. Uranium emits very energetic radiation – it is radioactive. Then Marie and Pierre Curie discovered more radioactive elements including polonium and radium. The most common types of radiation are called alpha (α), beta (β), and gamma (γ) radiation. But there are several other varieties of radioactive decay. Unstable nucleus by emitting radioactive particle (energy) becomes more stable.

**Radioactivity**

- Alpha radiation (decay)
  - Alpha particles emitted by radioactive nuclei consist of 2 protons and 2 neutrons bound together into a particle identical to a helium nucleus; hence is written $^{4}_{2}$He or $^{4}_{2}$α.
  - When an unstable nucleus decays by emitting an α-particle it loses 4 nucleons, 2 of them being protons.
    - The nuclear equation is: $^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + \alpha$.$^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He$
  - α decay occurs primarily among heavy elements because the nucleus has too many protons which cause excessive repulsion. In an attempt to reduce the repulsion, a helium nucleus is emitted.

Mass of parent > mass of daughter + mass of alpha
Difference = kinetic energy

**Beta radiation (decay)**

- Beta particles are high energy electrons emitted from the nucleus.
- But there are no electrons in the nucleus.
- What happens is this:
  - one of the neutrons changes into a proton (stays in the nucleus) and an electron (emitted as a β-particle).
  - This means that the proton number increases by 1, while the total nucleon number remains the same.

The nuclear equation is:
$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + 0_{-1}e + \nu$$

Antineutrino produced in beta decay is antiparticle of neutrino. It was in radioactive beta decay that the existence of the weak interaction was first revealed. Weak interaction causes the transmutation $p \rightarrow n$.
Neutrino was introduced into theory in 1930 due to the fact that energy was missing in observations of beta decay. Pauli theorized that an undetected particle was carrying away the observed difference between the energy.

Quite a number of antineutrinos are discovered streaming from the planet’s centre produced by natural radioactivity in the Earth responsible for the immense quantity of heat generated by Earth.

**Gamma radiation (decay)**

- Nucleus, just like the atom, possesses energy levels.
- In α and β decay, the product of decay is often nuclide in an excited state. The daughter nuclide then drops to its ground state by emitting a photon.
- Gamma-emission does not change the structure of the nucleus, but it does make the nucleus more stable because it reduces the energy of the nucleus.
- Nuclear energy levels are of the order of MeV hence the high energy of the emitted photon, and the frequencies $(f = E/h)$ correspond to gamma rays.

$$^{12}_{0}B \rightarrow ^{12}_{0}C + 0_{-1}e \rightarrow ^{12}_{0}C + \gamma + 0_{-1}e$$
Decay chains

A radioactive nuclide often produces a radioactive daughter nuclide. The daughter will also decay, and the process will continue until finally a stable nuclide is formed. This process is known as decay chain.

Ionising Properties

- Radiation ionises molecules by ‘knocking’ electrons off of them.
- As it does so, energy is transferred from the radiation to the material.
- To knock an electron out of an atom requires about 10 eV.

α-particle

Since the α-particle is massive, relatively slow-moving particle (up to 0.1 c) with a charge of +2e, it interacts strongly with matter. Alpha particles have energies of about 5 MeV so α-particle can ionize a lot of atoms before they loose all their KE, passing through just a few cm of air.

They cannot penetrate paper.

Can be very harmful since ionizing atoms of human tissue cause demage to the cells similar to burning.

β-particle

The β-particle is a much lighter particle than the α-particle and although they travel much faster (up to 0.9 c) they cause less intense ionisation than the α-particle. They have a charge of only –e so they are less reactive. The β-particle travels about 1 m in air before it is absorbed. It can be stopped by a few mm of Al or other metal.

γ - photon

A γ - photon moving at the speed of light interacts weakly with matter because it is uncharged and therefore it is difficult to stop. Very penetrating; never completely stopped, though lead (Pb) and thick concrete will reduce intensity.

The high energy also means that if they are absorbed by atomic electrons, they give electrons enough energy to leave the atom. So they are ionizing. As they pass easily through human tissue, gamma rays have many medical applications.

Properties

Alpha, Beta and Gamma

Properties 2

The diagram shows how the different types are affected by a magnetic field.

The alpha beam is a flow of positively (+) charged particles, so it is equivalent to an electric current.

It is deflected in a direction given by right-hand rule - the rule used for working out the direction of the force on a current-carrying wire in a magnetic field.

Beta particles are much lighter than the alpha particles and have a negative charge, so they are deflected more, and in the opposite direction.

Being uncharged, the gamma rays are not deflected by the field.

Nuclear radiation and health

α and β - particles have energies measured in MeV. To ionized an atom requires about 10 eV, so each particle can ionize 10^5 atoms before they have run out of energy.

When radiation ionizes atoms that are part of a living cell, it can effect the ability of the cell to carry out its function or even cause the cell wall to be ruptured. If a large number of cells that are part of a vital organ are effected than this can lead to death. In minor cases the effect is similar to a burn.

The amount of harm that radiation can cause is dependent on the number and energy of the particles.

When a gamma photon is absorbed the whole photon is absorbed so one photon can ionize only one atom.

However, the emmited electron has so much energy that it can ionize further atoms leading to damage similar to that caused by alpha and beta.
Very high dose: Can affect the central nervous system leading to loss of coordination and death within two or three days.

Medium dose can damage the stomach and intestines resulting in sickness and diarrhoea, and possibly death within weeks.

Low dose: Loss of hair, bleeding, and diarrhoea.

Safe dose: All ionizing radiation is potentially harmful, so there is no point below which it becomes totally safe. However, at very low levels the risk is small, and can be outweighed by the benefits gained when, for example, an x-ray is taken of a broken leg.

Long-term: There is some evidence that after exposure to radiation, the probability of getting cancer or having a child with a genetic mutation increases.

Cancer: Rapidly dividing cancer cells are very susceptible to the effects of radiation and are more easily killed than normal cells. In radiotherapy, nuclear radiation is used to cure cancer by killing the cancerous cells.

Protection against radiation

There are two ways we can reduce the effect of nuclear radiation: distance and shielding. Alpha and beta radiation have a very short range in air, so will not be dangerous a few meters away from the source. The number of gamma photons decreases proportional to $1/r^2$ (where $r$ is the distance from the source), so the further away you are, the safer you will be. Although alpha is the most ionizing radiation, it can be stopped by a sheet of paper (although that means that alpha is the most harmful if ingested). Beta and gamma are more penetrating, so need a thick lead shield to provide protection.

A radiation burn caused during radiotherapy for cancer

Detection of Radiation

- Geiger–Muller (GM) tube
- This can be used to detect alpha (open window), beta, and gamma radiation.

The ‘window’ at the end is thin enough for radiation to pass through. If radiation enters the tube, it ionizes the gas inside. The tube contains fixed electrodes, which attract electrons and ions produced by the passage through the chamber of high-speed particles. When the electrodes detect ions or electrons, a circuit is activated and a pulse is sent to a recording device such as a light.

Stability

- If you plot the neutron number $N$ against the proton number $Z$ for all the known nuclides, you get the diagram shown here.

The stable nuclides of the lighter elements have approximately equal numbers of protons and neutrons. However, as $Z$ increases the ‘stability line’ curves upwards. Heavier nuclei need more and more neutrons to be stable. Can we explain why?

- It is the strong nuclear force that holds the nucleons together, but this is a very short range force.
- The repulsive electric force between the protons is a longer range force.
- So in a large nucleus all the protons repel each other, but each nucleon attracts only its nearest neighbours.

More neutrons are needed to hold the nucleus together (although adding too many neutrons can also cause instability). There is an upper limit to the size of a stable nucleus; all the nuclides with $Z$ higher than 83 are unstable.

Half - life

- Suppose you have a sample of certain number of identical unstable nuclei.
- All the nuclei are equally likely to decay, but you can never predict which individual nucleus will be the next to decay.
- The decay process is completely random.
- Also, there is nothing you can do to ‘persuade’ one nucleus to decay at a certain time.
- The decay process is spontaneous.

Does this mean that we can never know the rate of decay?
- No, because for any particular radioactive nuclide there is a certain probability that an individual nuclide will decay.
- This means that if we start with a large number of identical nuclides we can predict how many will decay in a certain time interval.

\[
\text{rate of decay} \propto \text{number of nuclei}
\]
Half-life ($T_{1/2}$) is the time taken for one half of the nuclei present in any given radioactive sample to decay.

Radioactive decay is a random process. So, in practice, the curve is a 'best fit' of points which vary irregularly like this.

Definition 2

The half-life of a radioactive isotope is the time taken for the activity of any given sample to fall to half its original value.

Exponential Decay

- Any quantity that reduces by the same fraction in the same period of time will follow an exponential decay curve.
- The half life can be calculated from decay curves.
- Take several values and the take an average.

Example:

Cobalt–60 decays by beta emission and has a half-life of approximately 5 years. If a sample of cobalt–60 emits 40 beta particles per second, how many will the same sample be emitting in 15 years time?

After 5 years activity will be 20/sec (number of decays/sec).

After another 5 years it will be 10/sec.

Finally after a further 5 years it will emit 5 particles/sec.
Till now we have discussed only transmutations of one nuclei to another by emitting radioactive particle that occur only naturally.

**Induced (artificial) transmutation**

This change of one element to another through the bombardment of a nucleus is known as artificial transmutation.

Induced transmutation doesn’t mean it can not happen naturally – it means bombardment only

e.g., production of nitrogen from carbon in atmosphere or artificially induced in the lab

\[
\text{\frac{14}{7}N + \frac{1}{0}n \rightarrow \frac{14}{6}C + \frac{1}{1}p}
\]

### Transmutations Examples

Energy released in nuclear reaction or decay is found the same way as binding energy: first find mass difference

\[
\Delta m = \text{LHS} - \text{RHS} \quad \text{in u}
\]

and then

\[
E = \Delta m \times 931.5 \, \text{MeV}
\]

#### Energy released in a decay: \( A \rightarrow C + D \)

spontaneous decay: \( M > m_1 + m_2 \rightarrow \) binding energy of the decaying nucleus < binding energies of the product nuclei. The daughter is more stable. This is why radioactive decay happens with heavy elements lying to the right of maximum in the binding energy curve. Energy released is in the form of kinetic energy of the products.

\[
\text{\frac{228}{88}Ra} \rightarrow \text{\frac{222}{86}Rn} + \frac{4}{2}\alpha \quad M > m_1 + m_2, \quad \text{but}
\]

**total energy on the left = total energy on the right**

\[
M c^2 = m_1 c^2 + m_2 c^2 + KE_1 + KE_2
\]

#### \( \alpha \) – decay

Thorium – 228 decays by \( \alpha \) – emission:

\[
\text{\frac{228}{86}Th} \rightarrow \text{\frac{224}{88}Ra} + \frac{4}{2}\alpha
\]

Mass of thorium-228 nucleus = 227.97929 u

Mass of radium-224 nucleus + \( \alpha \)-particle = 223.97189 u + 4.00151 u

\[
= 227.97340 \, \text{u}
\]

\[
\Delta m = 227.97929 u - 227.97340 u = 0.00589 \, \text{u} = 5.49 \, \text{MeV}
\]

What happens to this binding energy? It appears mostly as kinetic energy of \( \alpha \) – particle. The radium nucleus also recoils slightly (and so momentum is conserved).
\( \beta \) – decay

Aluminum – 29 decays by \( \beta \) – emission:

\[
^{29}_{13}\text{Al} \rightarrow ^{29}_{14}\text{Si} + ^{0}_{-1}\beta + ^{0}_{0}\nu
\]

Mass of aluminum-29 nucleus = 28.97330 u

\[
\text{Mass of silicon-29 nucleus + } \beta\text{-particle + antineutrino = }
\]

\[
= 28.96880 \text{ u} + 0.000549 \text{ u} + 0 = 28.969349 \text{ u}
\]

\( \bowtie \) Mass difference = 28.97330 u – 28.969349 u = 0.003951 u = 3.68 MeV

Again this becomes the kinetic energy of the decay products.

Energy released in a nuclear reaction/artificial transmutation

Nuclear reactions \( A + B \rightarrow C + D \) can either

1. release energy

\[
\text{if } \Delta m = (m_A + m_B) - (m_C + m_D) > 0
\]

The total amount of energy released will be \( E = \Delta mc^2 \) in the form of kinetic energy of products. If there was initial kinetic energy, that will be added up to released energy.

2. or requires energy input

Nitrogen-14 will decay only if energy is supplied to it – collision with fast moving \( \alpha \) particle:

\[
^{14}_{7}\text{N} + ^{4}_{2}\alpha \rightarrow ^{17}_{8}\text{O} + ^{1}_{1}\text{p}
\]

\[
18.0057 \text{ u} < 18.0070 \text{ u}
\]

The \( \alpha \) particle must have enough kinetic energy to make up for imbalance in masses, and to provide for kinetic energy of products. This energy is supplied by a particle accelerator used to accelerate the helium nucleus.

Fission

- Fission means splitting up a large nucleus (\( A > 200 \)) into two smaller nuclei.
- the total BE would increase which means that the daughters are more stable than parent.
- The excess energy is released by the reaction.

- Spontaneous fission is very rare. Uranium is the largest nucleus found on Earth. Its isotopes will sometimes fission naturally. But half-life for \( \text{U-235} \) is 7.04x10^8 years
- Bombarding the nucleus with neutrons can trigger a fission reaction.
- For example

The strong forces that hold the nucleus together only act over a very short distance. When a uranium nucleus absorbs a neutron it knocks the nucleus out of shape. If the nucleus deforms enough, the electrostatic repulsion between the protons in each half becomes greater than the strong force. It then splits in two.

The nuclei splits randomly.

In the diagram, the fission fragments are shown as isotopes of Ba and Kr. This is just one of the many possible combinations.

Fission of a uranium nucleus gives out about 200 MeV of energy.

Chain Reactions

- When the uranium nucleus splits, a number of neutrons are also ejected.
- If each ejected neutron causes another uranium nucleus to undergo fission, we get a chain reaction
- The number of fissions increases rapidly and a huge amount of energy is released.
- Uncontrolled chain reactions are used in nuclear bombs
- The energy they unleash is devastating.
- Nuclear power stations use the heat released in carefully controlled fission reactions to generate electricity.
- They use control rods to absorb some of the neutrons.

- Fusion means joining up two small nuclei to form a bigger nucleus.
- When two small nuclei the product of fusion would have more BE per nucleon.
- The increases in binding energy per nucleon are much larger for fusion than for fission reactions, because the graph increases more steeply for light nuclei.
- So fusion gives out more energy per nucleon involved in the reaction than fission.
The stars are powered by fusion reactions.
Each second, in our Sun, more than 560 million tonnes of hydrogen fuse together to make helium.
One series of reactions for this is shown here:

Each small nucleus has a positive charge so they will repel each other. To make the nuclei come close enough for the strong force to pull them together, they must be thrown together with very high velocity. For this to take place, the matter must either be heated to temperatures as high as the core of the sun (about 13 million Kelvin) or the particles must be thrown together in a particle accelerator.

The energy released is radiated by the Sun at a rate of $3.90 \times 10^{20}$ MW.
This is the power output of a million million million large power stations!
Not surprisingly, scientists are keen to develop fusion as a source of power (fusion reactor).
One possible reaction is the fusion of deuterium and tritium.
These are isotopes of hydrogen.

Fusion has a number of advantages over fission:
- greater power output per kilogram,
- the raw materials are cheap and readily available,
- no radioactive elements are produced directly,
- irradiation by the neutrons leads to radioactivity in the reactor materials but these have relatively short half lives and only need to be stored safely for a short time.

So why don’t we use fusion in nuclear power stations?
The JET (Joint European Torus) project was set up to carry out research into fusion power.
It has yet to generate a self-sustaining fusion reaction.
The main problem is getting two nuclei close enough for long enough for them to fuse.

At this temperature all matter exists as an ionised gas or plasma.
Problem: containment. What can you use to hold something this hot?
JET (and Princeton) uses magnetic fields in a doughnut-shaped chamber called a torus to keep the plasma away from the container walls.
Unfortunately, generating high temperatures and strong magnetic fields uses up more energy than the fusion reaction produces!
The same problem is with accelerators, the path taken by Japan.
We are still some years off a fusion power station.

Applying the binding energy curve – checking stability

For example, consider the fission reaction:

\[ ^{238}_{92}U + ^{1}_{0}n \rightarrow ^{90}_{38}Sr + ^{166}_{76}U + 3^1_{1}n \]

The total binding energy of the uranium-238 nucleus is greater than the sum of binding energies of the tritium and deuterium nuclei. So, again as for fission, the system has effectively become more stable by losing energy.

\[ 2 \times 2 = 2 \text{ MeV} \]
\[ 2.8 \times 3 = 8.4 \text{ MeV} \]
\[ 4 \times 7 = 28 \text{ MeV} \]

Similarly for the fusion reaction:

\[ ^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{1}He + ^{1}_{0}n \]

The sum of the total binding energies of the fission nuclei is greater than the binding energy of the uranium-238 nucleus. Effectively, the system has become more stable by losing energy: \( KE_{\text{fusion}} \) provided that energy.