NUCLEAR PHYSICS - REVIEW
Atomic structure
Atomic structure
Nuclear structure
Radioactive Decay
Nuclear Reactions, Transmutations, Fission and Fusion
Atomic structure
- 1808 - John Dalton – new idea – the matter is made of tiny solid indivisible spheres like billiard balls - atoms

- 1897 – J. J. Thomson found the first *subatomic* particle - the electron

  → Thomson’s “plum-pudding” model

  the atom was a positive sphere of matter and the negative electrons were embedded in it

  ◀️ Scientists then set out to find the structure of the atom.
Ernest Rutherford got his students Geiger and Marsden to fire the fast moving \(\alpha\)-particles at very thin gold foil and observe how they were scattered.

Most of the \(\alpha\)-particles passed straight through the foil, some were slightly deflected, as expected, but to his surprise a few were scattered back towards the source.

**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, 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.)

no neutrons (AD 1911)

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

1919 – Ernest Rutherford finally discovered proton
Problems with Rutherford’s model:

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

Bohr's atomic model is an updated version of Rutherford's model. The main difference between the two is that Bohr's model is based on theories and lessons from quantum physics.

- Electrons occupy discrete energy levels only, called “stationary states.”
- Electrons in these stationary states do not emit EM waves as they orbit.
- Photon is emitted when an electron jumps from excited state to a lower energy state. Energy of that photon is equal to the energy difference between two states. $E_{\text{photon}} = \Delta E$

1932 – Chadwick discovered neutron
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 visualized 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.
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)
1. A hot solid, liquid or gas at high pressure produces a continuous spectrum – all $\lambda$.

2. A hot, low-density / low pressure gas produces an emission-line spectrum – energy only at specific $\lambda$.

3. A continuous spectrum source viewed through a cool, low-density gas produces an absorption-line spectrum – missing $\lambda$ – dark lines.

Thus, when we see a spectrum we can tell what type of source we are seeing.
Nuclear Structure

\[ r \approx (1.2 \times 10^{-15} \text{ m}) A^{1/3} \]
● 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 and neutrons in the nucleus.

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

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

● Neutron number - N (N = A – Z)
The number of neutrons in the nucleus.

● Symbol for a nucleid
$^A_X^Z X \quad ^7_3 Li$
Isotopes – Nuclei (atoms) of the same number of protons but different numbers of neutrons.

- 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 \( ^{238}\text{U} \)
- the current largest atomic number element, with atomic number 118, survived for less than a thousandth of a second
The strong nuclear force
What holds the nucleus together?

The mutual repulsion of the protons tends to push the nucleus apart. What then, holds the nucleus together?

The strong nuclear force. Strong nuclear force has much shorter range than electric.

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 \times 10^{-14} m) and is independent of charge and this is the reason the nucleus of an atom turns out to be so small.

The strong nuclear force was first described by the Japanese physicist Hideki Yukawa in 1935. It is the strongest force in the universe, 10^{38} times stronger than gravitational force and 100 times stronger than the electromagnetic force.
As nuclei get larger, more neutrons are required for stability.

The neutrons act like glue without adding more repulsive force.

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. 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.
The Mass Deficit of the Nucleus and Nuclear Binding energy
- Binding energy (BE) is energy required to separate the nucleus into individual free nucleons.

- Mass defect ($\Delta m$) is the difference between the mass of separated free nucleons and the mass of the nucleus.

Binding energy: mass deficit converted into energy
(heat, light, higher energy states of the nucleus/atom or other forms of energy).

\[
\text{BE (J)} = \Delta m(\text{kg}) \ c^2 \\
\text{BE (MeV)} = \Delta m(\text{u}) \times 931.5
\]

\[
c = 3 \times 10^8 \text{ m/s}
\]

\[
1 \text{u} \leftrightarrow 931.5 \text{ MeV}
\]

Unified Atomic Mass Unit (amu abbreviated as u) = 1/12 of the mass of one atom of carbon-12 (6p+6n+6e).

- 1 u = 1.66053886 x 10^{-27} kg

1 electron volt = 1.60217646 x 10^{-19} joules
binding energy per nucleon - the binding energy of a nucleus is divided by its mass number \( \frac{BE}{A} \)

BE of pure Fe is 8.7 MeV/nucleon. It is maximum BE.

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.
The most common types of radiation are called alpha ($\alpha$), beta ($\beta$), and gamma ($\gamma$) radiation.

But there are several other varieties of radioactive decay.

Unstable nucleus by emitting radioactive particle/energy becomes more stable.
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 as $^4_2\text{He}$ or $^4_2\alpha$.

- When an unstable nucleus decays by emitting an $\alpha$-particle it loses 4 nucleons, 2 of them being protons

\[
{^{226}_{88}\text{Ra}} \rightarrow {^{222}_{86}\text{Rn}} + {^4_2\text{He}}
\]

- The nuclear equation is:

\[
{^AX} \rightarrow {^{A-4}_{Z-2}Y} + {^4_2\alpha}
\]

$\alpha$ 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.
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) \textit{and} electron (emitted as a $\beta$-particle).
    - This means that the proton number increases by 1, while the total nucleon number remains the same.

The nuclear equation is:

\[
\begin{array}{c}
\text{A} \quad X \\
\text{Z} \\
\rightarrow \\
\text{A} \\
\text{Z+1} \\
Y \\
\quad + \\
\quad -1e \\
\quad + \\
\quad \nu
\end{array}
\]

\[
\begin{array}{c}
\frac{1}{0}n \\
\rightarrow \\
\frac{1}{1}p \\
\quad + \\
\quad -1e \\
\quad + \\
\quad \nu
\end{array}
\]

Neutrinos are created as a result of “beta plus” decay in which proton is converted via weak force to a neutron, a positron (antielectron) and a neutrino (nuclear fusion powering the sun and other stars.).
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.

\[
\begin{align*}
\text{^{12}_5B} & \rightarrow \text{^{12}_6C^*} + \text{^0}_{-1}e \\
& \rightarrow \text{^{12}_6C} + \gamma + \text{^0}_{-1}e
\end{align*}
\]
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.

\[
^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}\alpha \\
M > m_1 + m_2 \text{ , but}
\]

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

\[
Mc^2 = m_1c^2 + m_2c^2 + KE_1 + KE_2
\]
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

\( \alpha \)-particle

Since the \( \alpha \)-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 \( \alpha \)-particle can ionize a lot of atoms before they lose 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 damage to the cells similar to burning.

\( \beta \)-particle

The \( \beta \)-particle is a much lighter particle than the \( \alpha \)-particle and although they travel much faster (up to 0.9 c) they cause less intense ionisation than the \( \alpha \)-particle. They have a charge of only – e so they are less reactive. The \( \beta \)-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 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.
Half-life
Definition

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

\[ \begin{align*}
N_0 & \quad \text{Number of nuclei remaining} \\
N_0/2 & \\
N_0/4 & \\
N_0/8 & \\
\end{align*} \]

\[ \begin{align*}
t_{1/2} & \quad \text{time} \\
t_{1/2} & \\
t_{1/2} & \\
t_{1/2} & \\
\end{align*} \]
Activity and half-life

- It is much easier to measure the radiation than the number of undecayed nuclei in a sample.
- **Activity** (becquerel - Bq) of a radioactive sample is the average number of disintegrations per second.
- 100 Bq means that 100 nuclei are disintegrating/sec.

As the activity is always proportional to the number of undecayed nuclei, it too halves every 8 days.

Since the rate of decay is proportional to the number of nuclei, a graph of the rate of particle emission against time will have the same shape.

Activity of a sample of I -131.

\[ T_{1/2} = 8 \text{ days} \]

Original activity = 40 counts/sec
Radioactive decay is a random process. So, in practice, the curve is a ‘best fit’ of points which vary irregularly like this.
Example:

sample containing \(N\) radioactive atoms, grams, kilogram, moles, …

- after \(T_{1/2}\) \(N/2\) decayed
- after \(T_{1/2}\) \(N/2/2\) decayed
- after \(T_{1/2}\) \(N/2/2/2\) decayed …

after time \(nT_{1/2}\) only \(\frac{N}{2^n}\) survived

\[
\frac{N}{2} + \frac{N}{2^2} + \frac{N}{2^3} + \ldots + \frac{N}{2^n} \quad \text{transmutated}
\]

for example, after \(4T_{1/2}\) there is still \(\frac{N}{2^4} = \frac{N}{16}\) atoms in the sample (survived)

\[
\frac{N}{2} + \frac{N}{4} + \frac{N}{8} + \frac{N}{16} = \frac{15}{16}N \quad \text{transmutated}
\]
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.
Nuclear Reactions, Transmutations, Fission and Fusion
Natural transmutation (radioactivity)

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

example: production of nitrogen from carbon in atmosphere or artificially induced in the lab

\[ {^{14}_7}N + ^1_0n \rightarrow {^{14}_6}C + ^1_1p \]
● Alpha particle, neutrons, protons, and deuterons .... can be used to produce artificial nuclear reactions.

● The key to understanding these reactions and making predictions about the products of such reactions is being able to balance nuclear equations.

● For the nuclear equation: $A \rightarrow C + D$ or $A + B \rightarrow C + D$
  - nucleon and proton numbers must balance on each side of the equation.
  - conservation of total energy (energy + mass) must be satisfied

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

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

and then \[ E = \Delta m \times 931.5 \text{ (MeV)} \]
Energy released in a nuclear reaction/artificial transmutation

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

1. release energy
   
   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:

\[
\begin{align*}
\frac{14}{7}N + \frac{4}{2}\alpha &\rightarrow \frac{17}{8}O + \frac{1}{1}p \\
\Delta m &= (m_A + m_\alpha) - (m_O + m_p) < 0
\end{align*}
\]

\( \alpha \) 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 U-235 is $7.04 \times 10^8$ years.

Bombarding the nucleus with neutrons can trigger a fission reaction.

For example, bombarding a uranium nucleus ($^{235}\text{U}$) with a neutron ($^1\text{n}$) can cause the nucleus to split into two smaller nuclei, in this case, $^{141}\text{Ba}$ and $^{92}\text{Kr}$, plus three neutrons ($^{3}\text{n}$).

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 split 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

- 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.
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.
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.

- 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.
A scientist working inside JET’s 6 m diameter torus