An atom consists of protons, neutrons, and electrons.

1897 – J. J. Thomson discovered that all matter contains tiny negatively charged particles - electrons
=> plum pudding model of an atom

1919 – Ernest Rutherford discovered proton what led to
Rutherford/Planetary/Nuclear Model of atom:

- All of the positive charge was concentrated in a very tiny but very massive nucleus.
- Orbiting around this nucleus in circles are the electrons.
  (Electrons orbit nucleus as result of electrostatic attraction between the electrons and the nucleus. If they weren’t moving in an orbit, they would be attracted to the nucleus and move straight to it)

**evidence: Geiger and Marsden’s experiment:**

- Alpha particles bombarded at a thin sheet of gold foil mostly passed through—atoms mostly consist of empty space.
- Some of α particles were scattered back, so they concluded that that must have been caused by electrostatic repulsions between the positive alpha particles and a dense, small positive nucleus.

**limitations/problems:**
- Electrons orbiting nucleus are changing direction, and therefore accelerating
- According to Maxwell, any accelerating charge will generate an EM wave
- This EM wave would be a release of energy and give off light at all sorts of wavelengths.
- Electron releasing energy should slow down and eventually spiral into the nucleus.

**Bohr’s Model** - atomic energy levels

- Electrons could only exist in certain orbits at specific energy levels (“discrete states”), called “stationary states.” (we say energy of is quantized)
- Electrons in these stationary states do not emit EM waves as they orbit.
- \( n \) is called the principal quantum number and goes all the way up to infinity (\( \infty \))!

- If a photon of just the right energy strikes an atom, it is absorbed by the atom causing an electron to jump to a higher energy level: We say the atom is excited
  - Electron stays in higher energy level only for about 1 ns.
  - When the atom de-excites the electron jumps back to a lower energy level
These energies naturally lead to the explanation of the hydrogen atom spectrum:
Transitions between energy levels
• In its ground state or unexcited state, hydrogen’s single electron is in the 1st energy level (n = 1):
  - excitation: e⁻ absorbs energy
  - de-excitation: e⁻ emits energy
Energy of that photon is equal to the energy difference between two states. \( E_{\text{photon}} = \Delta E \)

Albert Einstein:
The frequency of emitted light (photon) is proportional to the change of energy of the electron:
\[
f = \frac{\Delta E}{h}
\]

Modern approach - Schrodinger wave function:
• energy level model - give possible energies of electrons and probability to find electrons somewhere is given by wave function.

Wave-particle duality: light acts like a (EM) wave, having a wavelength \( \lambda \) and a frequency \( f \), \( c = \lambda f \)
and it acts like a particle (photon) having an energy \( E \) given by \( E = hf \) (Planck’s constant \( h = 6.627 \times 10^{-34} \text{ Js} \))
emitted/absorbed photon has:
\[
E = hf = h \frac{c}{\lambda} \quad \text{&} \quad \lambda = h \frac{c}{E}
\]

Continuous Spectrum (without prism white light)
• a spectrum having all wavelengths over a comparatively wide range
• All possible frequencies of EM waves are present.
• Generally, solids, liquids, or high pressured (dense) gases emit a continuous spectrum when heated.

Line/Discrete spectrum - Evidence of electron energy levels
• Pattern of distinct lines of color, corresponding to particular wavelengths.

• Emission Spectrum
  • Set of frequencies of the electromagnetic waves
  • emitted by atoms of a particular element.
  • A hot, low-density / low pressure gas (gas in the atomic state) produces an emission-line spectrum – energy only at specific \( \lambda \).

• Absorption Spectrum
  • Pattern of dark lines against a continuous spectrum background that results from the absorption of selected frequencies by an atom or molecule.
  • An absorption spectrum occurs when light passes through a cold, dilute gas and atoms in the gas absorb at characteristic frequencies; since the re-emitted light is unlikely to be emitted in the same direction as the absorbed photon, this gives rise to dark lines (absence of light) in the spectrum.
**Atom:** the smallest amount of an element having the chemical properties of the element

**Nucleon:** a proton or neutron.

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

**Isotopes:** Nuclides contain the same number of protons but different number of neutrons. 

Isotopes are evidence for the existence of neutrons 
the same number of electrons – the same chemical properties 
different number of neutrons → different masses – different physical properties

\[
\begin{align*}
A & \quad \text{is the nucleon (mass) number = number of neutrons + protons} \\
Z & \quad \text{is the atomic number = number of electrons or protons} \\
A - Z & \quad \text{is number of neutrons}
\end{align*}
\]

**Repulsive electromagnetic force** between protons would cause a nucleus to disintegrate if it were the only force.

**Strong nuclear force** is an attractive force, which exists between all nucleons to hold them together. It acts only over short distances, about 1.5 radii of a proton or neutron and is independent of charge.

**Weak nuclear force** exists only in the nucleus and is responsible for the disintegration of a neutron into a proton and an electron in beta decay.

**Nuclear Stability:** depends on the neutron-proton ratio

- The strong short range nuclear force holds nucleons together in nuclei. It counteracts the long range repulsive force among protons contained within it. So in a large nucleus all the protons repel each other, but each nucleon attracts only its nearest neighbours. As long as the attractive nuclear forces between all nucleons wins 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.
  - Small nuclei- tend to have equal number of neutrons and protons
  - Large nuclei- tend to have more neutrons to counterbalance repulsive Coulomb force.
    - more neutrons are needed to hold the nucleus together (although adding too many neutrons can also cause instability).

The most massive isotope found in nature is uranium isotope \(^{238}\text{U}\).

For more massive nuclei (Z > 83) strong nuclear force can’t overcome electric repulsion, and those nuclides are unstable.

**Stability & Radioactive decay**

- Diagram: neutron number N against the proton number Z for all the known nuclides.
- The stable nuclides of the lighter elements have approximately equal numbers of protons and neutrons. Up to Z = 20, the neutron-to-proton ratio is close to 1.
- As Z increases the ‘stability line’ curves upwards. Beyond Z = 20, the neutron-to-proton ratio is bigger than 1, and grows with atomic number.
- Heavier nuclei need more and more neutrons to be stable.
  - The extra neutrons counteract the repulsive Coulomb force between protons by increasing the strong force but not contributing to the Coulomb force.
  - 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 protons repel each other, but each nucleon attracts only its nearest neighbours.
Radioactive Decay – Spontaneous decay of unstable nuclei.

- process in which unstable nucleus loses energy by emitting “radiation” in the form of particles or EM waves, resulting in transformation of parent nuclide into daughter nuclide.
- This is a random process on the atomic level, in that it is impossible to predict when a particular atom will decay, but given a large number of similar atoms, the decay rate, on average, is predictable.
- three common radiations - alpha, beta, gamma
  They differ in charge, ionization and penetration power.

α – Alpha Particle: \( ^{4}_{2}\text{He} \) or \( ^{4}_{2}\alpha \)
- nucleus consisting of 2 protons and 2 neutrons, when emitted from the nucleus of a radioactive atom.
- charge is \( +2e \)

Alpha decay: \( ^{4}_{2}X \rightarrow ^{4}_{2}Y + ^{4}_{2}\alpha \)
- nucleus ejects an α particle, the atomic number is decreased by 2 and the atomic mass is decreased by 4
- the most ionizing and therefore the least penetrating (a few cm of air)
- governed by strong nuclear force: 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

\( \beta^- \) beta minus particle: \( ^{0}_{-1}\text{e} \) or \( \beta^- \) electron emitted from the nucleus of a radioactive atom
- charge is \(-e\)

\( \beta^+ \) beta plus particle: \( ^{+}\text{e} \) or \( \beta^+ \) positron emitted from the nucleus of a radioactive atom
- charge is \(+e\)

Beta decay occurs when, in a nucleus with too many protons or too many neutrons, one of the protons or neutrons is transformed into the other. One or the other decay will move the product closer to the region of stability. A beta particle is either an electron (\( \beta^- \)) or an anti-electron (positron \( \beta^+ \)).
- it was discovered that beta particles could have a large variety of kinetic energies.
- medium ionizing and therefore medium penetrating (a few mm of metal)

Beta particles are a type of ionizing radiation and for radiation protection purposes are regarded as being more ionising than alpha particles, but less ionising than gamma rays. The higher the ionising effect, the greater the damage to living tissue.

Beta minus decay: \( ^{4}_{2}X \rightarrow ^{4}_{2}Y + ^{0}_{-1}\text{e} + \bar{\nu} \) most common decay
- occurs when the neutron to proton ratio is too great in the nucleus and causes instability
- the weak interaction converts a neutron into a proton, emitting an electron and an anti-neutrino:
  \( n \rightarrow p + e^- + \bar{\nu} \)
  \( ^{4}_{2}C \rightarrow ^{4}_{2}N + \beta^- + \bar{\nu} \)

Beta plus decay: \( ^{4}_{2}X \rightarrow ^{4}_{2}Y + ^{+}\text{e} + \nu \)
- occurs when the proton to neutron ratio is too great in the nucleus and causes instability; nucleus emits beta plus particle (positron) and a neutrino. Positron emission is mediated by the weak force.
- The \( \beta^+ \) particle and neutrino are ejected from the atom entirely, and the neutron remains
  \( p \rightarrow n + e^+ + \nu \)
  \( ^{23}_{12}\text{Mg} \rightarrow ^{23}_{11}\text{Na} + \beta^+ + \nu \) \( \beta^+ = e^+ \)

\( \gamma \) - Gamma particle: High-energy photon emitted from the nucleus of a radioactive atom

Gamma Decay: EM waves (high-energy photons) are emitted from a nucleus in an excited state dropping to a lower energy state (more stable)
- charge is 0
- the nucleus has less energy (it is more stable) but its mass number and its atomic number have not changed.
- no ionizing and therefore highly penetrating (a few cm of lead)

\( ^{12}_{5}\text{B} \rightarrow ^{12}_{6}C^* + ^{0}_{-1}\text{e} \rightarrow ^{12}_{6}C + \gamma + ^{0}_{-1}\text{e} \)
**Biological effects of ionizing radiation:**
- **Prompt effects:** effects, including radiation sickness and radiation burns, seen immediately after large doses of radiation delivered over short periods of time.
- **Delayed effects:** effects such as cataract formation and cancer induction that may appear months or years after a radiation exposure.

**Radioactive Decay** is a random process on the atomic level, in that it is impossible to predict when a particular atom will decay, but given a large number of similar atoms, the decay rate, on average, is predictable. The rate of decay decreases exponentially with time.

**Nuclear Reaction:** A reaction that occurs whenever the number of protons or neutrons changes. Nuclear reactions include natural and artificial transmutation, fission, and fusion.

**Transmutation:** change of one element into another.
- In order to balance nuclear reaction the total mass and total charge number of the reactants has to equal the total mass (mass + energy) and total charge number of the products.
  - In *natural transmutation* the nucleus decays spontaneously. There is only one nucleus that undergoes the transformation.
  - *Artificial transmutation* is induced by the bombardment of the nucleus by high-energy particles (Uranium atoms bombarded with neutrons to start fission reaction.)

**Radioisotope:** an isotope of an element that is radioactive

**Radioactive Dating:** method of estimating the age of an object based on the object’s half-life and the amount of isotope present. Carbon dating is limited to the dating of organic (once living) materials.

**(Artificial) Radioactivity:** the (induced) spontaneous breakdown of atomic nucleus with emission of particles and energy (rays).

**Half – life** $T_{1/2}$ is the interval of time required for one-half of the atomic nuclei of a radioactive sample containing $N$ radioactive atoms, grams, kilograms, moles,... after $T/2$ $N/2$ decayed after $T/2$ $N/2/2$ decayed after $T/2$ $N/2/2/2$ decayed ...

\[
\text{after } \frac{T}{2} \text{ time, only } \frac{N}{2^4} \text{ survived, and } \frac{N}{2} + \frac{N}{2^2} + \frac{N}{2^3} + \frac{N}{2^4} = \left( \frac{N}{2^4} \right) = \frac{15}{16} N \text{ transmutated}
\]

**Activity** (becquerel - Bq) of a radioactive sample is the average number of disintegrations per second.

- It is much easier to measure the radiation than number of undecayed nuclei in a sample.

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.
Unified Atomic Mass Unit (u) is 1/12 of the mass of one atom of carbon-12 atom (6p+6n+6e)
• 1 u = 1.66056655 x 10^{-27} kg
• 1 u of mass converts into 931.5 MeV (due to relationship E = mc^2 → 1 u = 931.5 MeV c^2)

Mass Defect (δ) difference in mass between the sum of the masses of the (free) nucleons from which nucleus was made and the actual mass of an atomic nucleus (nuclide).
• Total mass of a nucleus < sum of masses of nucleons
• mass defect = total mass of nucleons – mass of nucleus > 0
  \[ \delta = Zm_p + Nm_n - M_{\text{nucleus}} \]
  can be calculated in kg or u. Equivalent to binding energy.

Binding Energy is the work required to completely separate the nucleons of a nucleus/ energy released when nucleons form a nucleus.
• Energy that must be applied to a nucleus to break it up into separate, free particles
• A bound system has a lower potential energy than its constituent parts; this is what keeps the nucleus together.
• nuclear binding energy is actually energy that corresponds to mass defect
1. BE in MeV: find mass defect in u and multiply it by 931.5 MeV
2. BE in J: \[ BE = \delta c^2 \] (c = 3x10^8 m/s, \( \delta \) = mass defect in kg)

Binding Energy per Nucleon is energy required to remove 1 nucleon from the nucleus
• is roughly the binding energy divided by total number of nucleons
• The binding energy of a nucleus is a measure of how stable nucleus is. Greater mass defect – higher binding energy – greater stability.
• Most nuclei have a binding energy per nucleon of approximately 8 MeV.

Energy released/required in a nuclear reaction/artificial transmutation
• In order to balance nuclear reaction the total mass/energy and total charge number of the reactants has to equal the total mass/energy and total charge number of the products.
• Nuclear reactions \( A + B \rightarrow C + D \) can either release energy or requires energy input.
• \( \Delta m = (m_A + m_B) - (m_C + m_D) = \text{LHS} - \text{RHS} \)
• release of energy: Energy will be released in nuclear reaction if \( \Delta m = \text{LHS} - \text{RHS} > 0 \)
• total amount of energy released, \( E = \Delta mc^2 \), will be in the form of kinetic energy of products.
• energy released in nuclear reaction is found the same way as binding energy: first find mass difference and then equivalent energy
  \( \Delta m \) in u, \( E = (\Delta m) \times 931.5 \text{ (MeV)} \) or \( \Delta m \) in kg, \( E = (\Delta m) c^2 \) (J)
• If there was initial kinetic energy, that will be added up to released energy
• energy input: if \( \Delta m = \text{LHS} - \text{RHS} < 0 \), reaction cannot be spontaneous.
  For example, some nuclei will decay only if energy is supplied to it - collision with fast moving α particle: Nitrogen-14 will decay only if energy is supplied to it - collision with fast moving α particle:
  \[ 18.0057 \text{ u} < 18.0070 \text{ u} \]
  \( \Delta m = (m_A + m_\alpha) - (m_C + m_0) < 0 \)
  α particle must have enough KE to make up for imbalance in masses, and to provide for kinetic energy of products.
**Energy released in a decay** - conservation of total energy (energy + mass). as always

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

*total energy on the left = total energy on the right* \[ M c^2 = m_1 c^2 + m_2 c^2 + KE_1 + KE_2 \]

- **spontaneous decay**: \( M > m_1 + m_2 \rightarrow\) binding energy of the decaying nucleus < binding energies of the product nuclei.

  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.

**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.

**Nuclear fission**: process in which a large nucleus (A>200) splits up into two smaller nuclei, generally accompanied by the release of one or more neutrons and energy (as gamma rays and as kinetic energy of the fragments).

- Large amounts of energy produced, can be self-sustaining due to chain reactions.
- The total BE would increase which means that the daughters are more stable than parent (look at the graph).
- Fission can occur when a nucleus of a heavy atom captures a neutron, or it can happen spontaneously.
- 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 7.04x10^8 years.
- Bombarding the nucleus with neutrons can trigger a fission reaction.
- For example

  ![Diagram of Uranium Fission](image)

  The strong forces that hold the nucleus together only act over a very short distance.

  When a uranium nucleus absorbs a neutron (U-235 → U-236) 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.

  **Nuclear fusion**: joining up of two small nuclei into a bigger one, releasing great amounts of energy in the process.

  - High temperatures are required to provide sufficient kinetic energy to approach each other, overcoming electrostatic repulsion.
  - 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.

- 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.

### 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 emitted 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 diarrhea, and possibly death within weeks.
- Low dose: Loss of hair, bleeding, and diarrhea.
- 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 affect 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 gama 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.
**Description and classification of particles**

- **An elementary particle** has no internal structure.

In particle physics, an elementary particle or fundamental particle is a subatomic particle with no substructure, thus not composed of other particles.

Particles currently thought to be elementary include the fundamental fermions (quarks, leptons, antiquarks, and antileptons), which generally are "matter particles" and "antimatter particles", as well as the fundamental bosons (gauge bosons and the Higgs boson), which generally are "force particles" that mediate interactions among fermions. A particle containing two or more elementary particles is a composite particle.

- **The force carriers/gauge bosons** are the particles that allow compatible particles to sense and react to each other's presence through exchange of these carriers.

- **The quarks** are the heavier, tightly bound particles that make up particles like protons and neutrons.
- **The leptons** are the lighter, more loosely bound particles like electrons.

**Fundamental forces and their properties**

<table>
<thead>
<tr>
<th>Force Carrier:</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range:</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>Extremely Short</td>
</tr>
<tr>
<td>Force Carrier:</td>
<td>Gluon</td>
<td>Photon</td>
<td>Graviton</td>
</tr>
</tbody>
</table>

| Range:         | 1.0              | 0.01             | 0.000001         | $10^{-39}$ |
| Force Carrier: | Strongest        | Electro-Weak     | WEakest          |

**The nature and range of the force carriers**

- In 1933 Hideki Yukawa developed the theory of exchange forces.
- The basic idea is that all forces are due to the exchange of particles between like elementary particles.
- Consider two protons in space. **Yukawa postulated that the protons exchange photons and repel each other because of this exchange.**
- **This photon exchange is the electromagnetic force.**
- Yukawa explained that the electromagnetic force was long range (in fact infinite in range) because photons "live forever" until they are absorbed.
- Yukawa explained that the strong force was short range (in fact only in the nuclear range) because the strong force exchange particle (the **gluon**) has a very short life.

LONG RANGE EXCHANGE PARTICLE

SHORT RANGE EXCHANGE (VIRTUAL) PARTICLE
• Exchange particles whose range of influence is limited are called **virtual particles**.

The four fundamental forces have different ranges and a different gauge boson is responsible for each force. The mass of the boson establishes the range of the force. The bosons carry the force between particles.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Range</th>
<th>Exchange Particle</th>
<th>Rest Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>$10^{-5}m$</td>
<td>Gluon g</td>
<td>$120\text{ MeV/c}^2$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$\infty$</td>
<td>Photon $\gamma$</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-18}m$</td>
<td>$W^+, W^-$ and $Z$</td>
<td>80 GeV/c²</td>
</tr>
<tr>
<td>Gravitation</td>
<td>$\infty$</td>
<td>Graviton Y</td>
<td>0</td>
</tr>
</tbody>
</table>

• Virtual particles can only exist within their range of influence.

**Quarks and their antiparticles**

• In 1964 the particle model was looking quite complex and unsatisfying. Murray Gell-Mann proposed a model where all the strong-force particles were made up of three fundamental particles called **quarks**.

<table>
<thead>
<tr>
<th>Charge</th>
<th>Quarks</th>
<th>Baryon number</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2/3) e</td>
<td>u</td>
<td>1/3</td>
</tr>
<tr>
<td>-(1/3) e</td>
<td>d s b</td>
<td>1/3</td>
</tr>
</tbody>
</table>

All quarks have a strangeness number 0 except the strange quark that has strangeness number of $-1$.

• Every particle has an antiparticle which has the same mass but all of its quantum numbers are the opposite.
• Thus an antiproton ($\bar{p}$) has the same mass as a proton ($p$), but the opposite charge (-1).
• When matter meets antimatter both annihilate each other to become energy!

  proton is $uud$
  neutron is $udd$

**Hadrons, baryons, and mesons**

A **hadron** is a particle that participates in the strong force.
A **baryon** is made of three quarks (qqq). An antibaryon is made of three antiquarks ($\bar{q}\bar{q}\bar{q}$).
A **meson** is made up of a quark and an antiquark ($q\bar{q}$):

Since quarks participate in the strong force, and since baryons and mesons are made of quarks, baryons and mesons are hadrons.

• **Quark confinement** means that we cannot ever separate a single quark from a baryon or a meson.
• Because of the nature of the strong force holding the quarks together we need to provide an energy that is proportional to the separation.
• Eventually, that energy is so vast that a new quark-antiquark pair forms and all we have is a meson, instead of an isolated quark!

**Protons and neutrons in terms of quarks**

• A proton is a baryon made out of two up quarks and a down quark.
  $p = (uud)$. A proton is a hadron. Why?
• A neutron is a baryon made out of one up quark and two down quarks.
  $n = (udd)$. A neutron is also a hadron.

**EXAMPLE**: Show that the charge of a proton is +1, and that the charge of a neutron is 0.

  • The charge of an up quark is +2/3.
  • The charge of a down quark is -1/3.
  • Proton = uud : $+2/3 + 2/3 − 1/3 = +1$.
  • Neutron = udd : $+2/3 − 1/3 − 1/3 = 0$. 
**Conservation of baryon number**

In order to explain which particles can exist and to explain the outcome of observed interactions between particles, the quarks are assigned properties described by a numerical value. The quark is given a baryon number B of 1/3. The antiquark is given a baryon number B of -1/3.

**PRACTICE:** What is the baryon number of a proton and an antiproton?

- **Proton** = \( uu\bar{d} \):
  
  \[
  \frac{1}{3} + \frac{1}{3} + \left(\frac{1}{3}\right) = +1
  \]

- **Antiproton** = \( u\bar{u}d\bar{d} \):
  
  \[
  \left(\frac{1}{3}\right) + \left(-\frac{1}{3}\right) + \left(-\frac{1}{3}\right) = -1
  \]

Like charge, baryon number is conserved in all reactions.

**Conservation of strangeness**

- The *strangeness number* \( S \) of a baryon is related to the number of strange quarks the particle has.

\[
S = \text{# antistrange quarks} - \text{# strange quarks}
\]

**EXAMPLE:** The lambda zero particle \((\Lambda^0)\) is a baryon having the quark combo of \((uds)\). What is its charge?

- From the table the charges are \( u = +2/3 \), \( d = -1/3 \) and \( s = -1/3 \) so that the total charge is 0.

\[
S = \text{# antistrange quarks} - \text{# strange quarks} = 0 - 1 = -1
\]

**EXAMPLE:**

When a \(K^-\) meson collides with a proton, the following reaction can take place.

\[
K^- + p \rightarrow K^0 + K^* + X
\]

\( X \) is a particle whose quark structure is to be determined. The quark structure of mesons is given.

(a) State and explain whether the original \(K^-\) particle is a hadron, a lepton or an exchange particle.

- The \( K^- \) is a hadron because it is composed of quarks.

(b) State the quark structure of the proton.

- The proton is composed of \( uud \)

(c) The quark structure of particle \( X \) is \( sss \). Show that the reaction is consistent with the theory that hadrons are composed of quarks.

\[
s\bar{u} + uud \rightarrow d\bar{s} + u\bar{s} + sss.
\]

- The left has an \( s, u, \) and \( d \) left.
- The right also has an \( s, u, \) and \( d \) left.
- The quarks are balanced on each side.
Leptons and their antiparticles

- You are already familiar with two of the six leptons: the electron and the electron neutrino ($\beta^-$ decay).
- Leptons, unlike hadrons (baryons and mesons), do NOT participate in the strong interaction.

<table>
<thead>
<tr>
<th>LEPTONS</th>
<th>charge</th>
<th>electron $e^-$</th>
<th>muon $\mu^-$</th>
<th>tau $\tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron neutrino $\nu_e$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>muon neutrino $\nu_\mu$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tau neutrino $\nu_\tau$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For each particle there is a corresponding antiparticle with a charge opposite that of its associated particle.

- The leptons interact only via the electromagnetic force carrier, the photon.
- Leptons, unlike quarks, do not react to the gluon.
- Quarks react to both the gluon and the photon.
- Leptons and quarks also react to gravitons.
- Of course the leptons also have their antiparticles.

STANDARD MODEL of ELEMENTARY PARTICLES

- The following graphic shows part of an organizational structure for particles called the standard model.

- These are the quarks from which mesons and hadrons are formed.
- Particles are divided into “generations” or “families” of increasing mass.

- These are the leptons, the most common of which is the electron.
- Muons are created in upper atmosphere by cosmic rays. Tau particles are created in the laboratory.
**conservation rules in reactions**
- charge is conserved
- baryon number is conserved
- lepton number is conserved
- strangeness is conserved

**Applying conservation laws in particle reactions**

PRACTICE: Find the lepton number of an electron, a positron, an antielectron neutrino, an antimuon neutrino, a tau particle, and a proton:

SOLUTION:
- An electron has a lepton number of \( L = +1 \).
- A positron is an antiparticle and so has \( L = -1 \).
- An antielectron neutrino has \( L = -1 \).
- An antimuon neutrino has \( L = -1 \).
- A tau particle has \( L = +1 \).
- A proton is not a lepton and so has \( L = 0 \).

**Worked examples**

1. a) Show that, when a proton collides with a negative pion (\( \bar{u}\bar{d} \)), the collision products can be a neutron and an uncharged pion.

   b) Deduce the quark composition of the uncharged pion.

   This suggests that the neutral pion is very short lived – since the combination \( u\bar{u} \) would mutually annihilate. In fact this particle has a lifetime of about \( 8 \times 10^{-17} \) s and annihilates to form two gamma ray photons or, very occasionally, a gamma ray photon, an electron and a positron.

2. Explain whether a collision between two protons could produce two protons and a neutron.

**Solution**

a) The equation for the interaction is
   \[ p + \pi^- \rightarrow n + \pi^0 \]
   \[ Q: +1 -1 \rightarrow 0 + 0 \]
   \[ B: +1 + 0 \rightarrow +1 + 0 \]
   \[ L: 0 + 0 \rightarrow 0 + 0 \]
   This interaction is possible on the basis of conservation of charge, baryon number and lepton number.

b) Writing the equation in terms of quarks:
   \[ u\bar{u}d + \bar{u}\bar{d} \rightarrow d\bar{d}u + ?? \]
   ?? = \( u\bar{u} \) in order to balance this equation.

**Solution**

Writing the equation for the baryons:
   \[ p + p \rightarrow p + p + n \]
   \[ Q: +1 +1 \rightarrow +1 + 1 + 0 \]
   \[ L: 0 + 0 \rightarrow 0 + 0 + 0 \]
   \[ B: +1 + 1 \rightarrow +1 + 1 + 1 \]
   So this interaction fails on the basis of baryon number.
**Feynman diagrams**

- Richard Feynman developed a graphic representation of particle interactions that could be used to predict the probabilities of the outcomes of particle collisions.
- A typical Feynman diagram consists of two axes: Space and Time:

![Feynman Diagram](image)

- Some books switch the space and time axis. The IB presentation is as shown above.
- Consider two electrons approaching one another from the top and the bottom of the page...
- A purely spatial sketch of this interaction would look like this:

![Electron Sketch](image)

- But if we also apply a time axis, the sketch would look like this:
  - The Time axis allows us to draw the reaction in a spread-out way to make it clearer.
  - The “bubble of ignorance” is the actual place in the plot that exchange particles do their thing.
  - Ingoing and outgoing particles are labeled.

- **Particles** are represented with straight arrows, as were the two electrons in the previous electron-electron interaction.
- **Exchange (force) particles** are represented with either wavy lines (photons, W⁺, W⁻ and Z⁰), or curly lines (gluons).
- You may have noticed that the electromagnetic exchange particle and the weak exchange particles all have the same wavy symbol.
- Indeed, it has been found that the two forces are manifestations of a single ELECTRO-WEAK force.
EXAMPLE:
• The complete Feynman diagram showing the repulsion of two electrons looks like this:

EXAMPLE:
• Here is a diagram for one electron emitting a photon:

EXAMPLE:
• Here is a photon producing an electron-positron pair.

EXAMPLE:
• Here is an electron-positron pair annihilating to become a photon.

EXAMPLE: Explain what has happened in this Feynman diagram.

SOLUTION:
• The up quark of a proton (uud) emits a gluon.
• The gluon decays into a down quark and an anti-down quark.

• Quarks cannot exist by themselves. Thus the two quarks produced above will quickly annihilate.

EXAMPLE: Write the reaction (including the neutrino) for beta (+) decay.

SOLUTION: \( p \rightarrow n + e^+ + \nu_e \)

EXAMPLE: Now draw the Feynman diagram for the above \( \beta^+ \) decay:
• Why is the neutrino not an anti-neutrino as in the \( \beta^- \) decay?
• To conserve lepton number.

EXAMPLE: Explain what has happened in this Feynman diagram.

SOLUTION:
• It is a diagram of a down quark emitting a W⁻ particle that decays into an electron and an antineutrino:

• One can use Feynman diagrams to map out complete processes – including the bubble of ignorance. Using the conservation rules and the exchange particles, you can predict what kind of processes can occur.

EXAMPLE: Explain what has happened in this Feynman diagram.

SOLUTION:
• Recall that a neutron consists of an up-down-down quark combo.
• Recall that a proton consists of an up-up-down quark combo.
• This is non other than the beta decay (\( \beta^- \)) we talked about a long time ago.

EXAMPLE: Now draw the Feynman diagram for the above \( \beta^- \) decay:
• Why is the neutrino not an anti-neutrino as in the \( \beta^- \) decay?
• To conserve lepton number.

EXAMPLE: In a Feynman diagram, antimatter points backward in time. This diagram represents two positrons repelling each other:

EXAMPLE: Here is a diagram for one positron emitting a photon:
**Worked example**

Draw Feynman diagrams to show the following interaction:

a) positive beta (positron) decay: \( p \rightarrow n + e^+ + \nu_e \)

b) proton–electron collision: \( p + e^- \rightarrow n + \nu_e \)

c) the two types of neutron–electron neutrino collision: \( n + \nu_e \rightarrow \nu_e + n \) and \( n + \nu_e \rightarrow p + e^- \)

**Solution**

a) ![Feynman diagram for positive beta (positron) decay.](image1)

In this decay the proton decays into a neutron and emits a positron and electron neutrino. The decay is mediated by the positive W boson (W⁺).

b) ![Feynman diagram for proton–electron collision.](image2)

In this case the proton and the electron collide and produce a neutron and an electron neutrino. This interaction is mediated by the W⁻ boson.

c) ![Feynman diagram for neutron–electron neutrino collision.](image3)

The most likely collision between a neutron and an electron neutrino is one in which the Z⁰ boson mediates the collision and the neutrino effectively bounces off the electron – this is known as a neutral current interaction. The electron neutrino can occasionally also interact through the W boson by changing a neutron into a proton. These are the charged current interactions.