Particle Physics

A-level Physics

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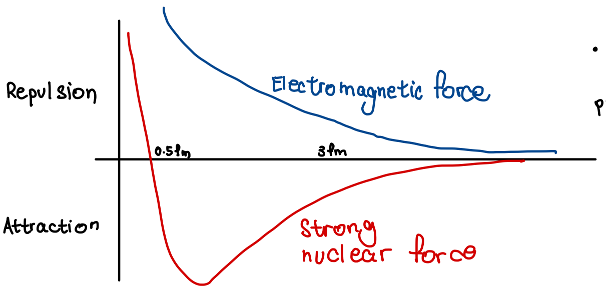
Stable and Unstable Nuclei

Forces in the nucleus:

- Electromagnetic force causes protons in the nucleus to repel
- Gravitational force causes nucleons (protons & neutrons) to attract each other
- Strong nuclear force to combat the electromagnetic force to hold the nucleus together.



- The nuclear force is repulsive up to 0.5fm to prevent it crushing the nucleus
  - Past 0.5fm, the strong nuclear force becomes attractive

What makes the nucleus unstable?

- The range of the strong nuclear force is only a few femtometres. It struggles to hold together very large nuclei, which makes them unstable.
- Unstable nuclei will emit particles to become more stable – known as nuclear decay.

Alpha decay

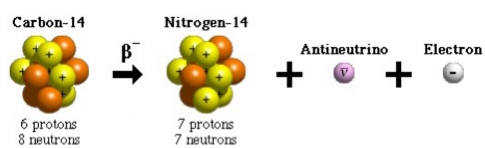
- Happens in very big atoms – as the nuclei of these atoms are too big for the strong nuclear force to keep them stable
- An alpha particle is emitted : ${}^{4}_{2}\alpha$ (contains 2 protons and 2 neutrons – helium nucleus)

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

Beta-minus decay (β^-)

- Happens in isotopes that are "neutron rich"
- An electron & an antineutrino particle are emitted
- One neutron is changed into a proton
- This leaves the element positively charged

1 less electron



$${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}W + {}^{0}_{-1}\beta + \bar{\nu}_e$$

(neutron → proton) (electron) (antineutrino)

this is needed due to lepton number conservation

Positron emission / Beta-plus decay (β^+)

- Takes place in an unstable nucleus with too many protons - "proton-rich".
- A proton changes into a neutron.
- The positron (β^+) is the antiparticle of the electron, so it carries a positive charge.

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}\beta + v_e$$

- PET scanning involves a positron-emitting isotope.

Gamma decay/radiation

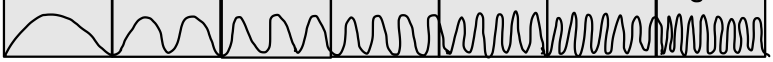
- It is electromagnetic radiation emitted by an unstable nucleus.
- It is emitted by a nucleus with too much energy.
- Gamma radiation has no mass and no charge. It can pass through thick metal plates.

Photons

Electromagnetic radiation

- The electromagnetic spectrum is a continuous spectrum of all the possible frequencies of electromagnetic radiation.
- The frequency of a wave is the number of complete waves passing a point per second.
- The wavelength of a wave is the distance between two adjacent crests of a wave.

Radio Waves	Micro-waves	Infra-red	Visible Light	Ultra-violet	X-Rays	Gamma Rays

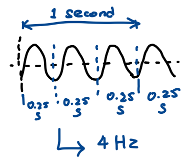


How is the wave speed equation derived?

$\boxed{\text{frequency}_{(Hz)} = \frac{1}{\text{Period}_{(s)}}}$

- Period is time taken for one wave cycle

→ The number of wave cycles per second = $\frac{1}{\text{Time taken for one oscillation}}$



$\xrightarrow{\text{Rearrange}}$ $\boxed{\text{Period}_{(s)} = \frac{1}{\text{Frequency}_{(Hz)}}}$

Substitute Period being time taken

$\boxed{\text{speed}_{(ms^{-1})} = \frac{\text{Distance (m)}}{\text{Time (s)}}}$ $\xrightarrow[\text{and Wave Time (Period)}]{\text{Substitute Wave Distance}}$ $\boxed{\text{Wave Speed} = \frac{\text{Wave Distance / Wavelength } (\lambda)}{\text{Time taken for one wavelength / Period}}}$

Since speed of a wave = c (proven in a vacuum)

$\boxed{c = \frac{\lambda}{\frac{1}{f}}}$ $\xrightarrow{\text{Rearranged}}$ $\boxed{c = f\lambda}$ ← Wave Speed Formula

Photons

When are electromagnetic waves emitted?

- Electromagnetic waves are emitted by a charged particle when it loses energy:
  - ↳ A fast moving electron is stopped / slows down.
  - ↳ An electron in an atom moves to a lower shell / energy level.

What the HECK is a photon?!

- Photon is the quantum (plural: quanta) (discrete packet) of the electromagnetic radiation and the force carrier for the electromagnetic force.
- To put more simply: photons are packets of EM waves and energy. (waves carry energy through vibrations)
- e.g Since visible light belongs to the EM spectrum, photons are the smallest components of light. → A photon is a quantum (discret packet) of light.
- Photons are massless → they travel at c. (speed of light)

The energy of one photon is: $\boxed{E = hf}$

- h: Planck's constant = 6.63×10^{-34} Js
- f: frequency of light (Hz) = colour / wave type
- E: Energy of a photon (J)

The wave speed equation rearranged: $\boxed{f = \frac{c}{\lambda}}$

Substitute f into $E = hf$

Alternative equation to find energy of one proton.

$$\boxed{E = hf = \frac{hc}{\lambda}}$$

How are quanta (discrete packets) discovered?

- When Max Planck was investigating black body radiation, he suggested that EM waves can only be released in discrete packets, or quanta.
- Einstein went further y suggesting that EM waves and their energy can only exist in discrete packets.
- The photon theory was established by Einstein in 1905, when he used his ideas to explain the photoelectric effect. (the emission of electrons from a metal surface when light is directed at the surface)

How is laser power calculated?

works by excitement of electrons in energy levels of atoms

- A laser (Light Amplification by Stimulated Emission of Radiation) beam consists of photons of the same frequency.
- The power of a laser beam is the energy per second transferred by the photons, for a beam consisting of photons of frequency f:

$$\boxed{\text{The power of the beam} = \underbrace{n}_{\text{number of photons in the beam passing a fixed point each second}}\underbrace{hf}_{\text{energy of each photon}}}$$

- From GCSE: power is the amount of energy per second.

$$\boxed{P = \frac{W}{\Delta t}}$$

E = hf and lasers

- According to $E = hf$, violet/purple has a higher frequency than red and hence carries way more energy.

↓ hence

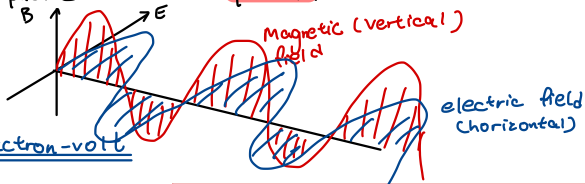
- Blue and green lasers are banned as they carry A LOT of energy in terms of photons.
- Red lasers are hence most widely used and the safest.

What is a wave really?

- They are a transfer of energy without the transfer of matter.
- Eg. Sound waves transfer energy by vibrations through air.

How are EM waves passed through without vibrations?

- EM radiation is emitted as a burst or "packet" (quantum) of waves with interlocking electric field (E) and magnetic field (B) oscillations at right angles to one another.
- These wave packets are called photons.



Joules vs electron-volt

- We calculate the kinetic energy of a charged particle by $E = QV$.

↓ however

- In particle physics the charges of 1 (or small amounts) of electrons/other particles are so small, this will result in extremely small joule values and hence kinetic energy is calculated in electron-volts.

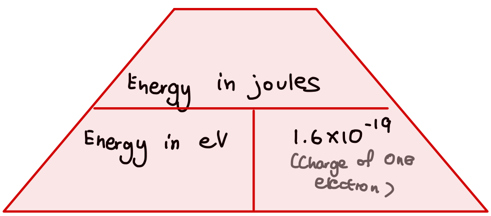
$$\boxed{1 \text{ electron-volt} = 1.6 \times 10^{-19} \text{ Joules}}$$

$$\boxed{E_{\text{Kinetic Energy}} = QV}$$

Lots and lots of charge of electrons (in coulombs)

$$\boxed{E_{\text{Kinetic Energy}} = eV}$$

Charge of an electron (number of electrons)



Particles and antiparticles

Antimatter

energy when particle is not moving

- Each particle type has a corresponding antiparticle with the same mass and rest energy but with opposite charge (if charged).
- All particles are known as matter and antiparticles are known as antimatter.

Mass increases as kinetic energy increases ($E = mc^2$)

How is antimatter discovered?

Particle/ Antiparticle	Symbol	Relative Charge	Mass (kg) (Resting)	Rest Energy (MeV)
proton	p	+1	$1.67(3) \times 10^{-27}$	938(.3)
antiproton	$\bar{p}$	-1		
neutron	n	0	$1.67(5) \times 10^{-27}$	939(.6)
antineutron	$\bar{n}$			
electron	e^-	-1	9.11×10^{-31}	0.51(1)
positron	e^+	+1		
neutrino	V_e	0	0	0
antineutrino	$\bar{V}_e$			

These two are equivalent (only units are changed)

Due to $\rightarrow E = mc^2$

- Antimatter was predicted in 1928 by English physicist Paul Dirac.
- Einstein had shown that the mass of a particle increases the faster it travels due to $\boxed{E = mc^2}$ (energy and mass is equivalent)
- Einstein said that the mass of a stationary particle (rest mass) (m_0) corresponds to rest energy ($m_0 c^2$) locked up as mass.
- Dirac predicted the existence of antiparticles that would unlock rest energy during annihilation (a particle or corresponding antiparticle meet).

Dirac's theory of antiparticles

- For every type of particle, there is a corresponding antiparticle that:
  - ↳ annihilates the particle and itself if they meet, converting their total mass into photons.
  - ↳ has same rest mass as the particle.
  - ↳ has opposite charge to the particle.
- Pair production: A photon with sufficient energy passing near a nucleus or an electron can change into a particle-antiparticle pair.

What are electron volts (MeV)?

$\boxed{1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}}$

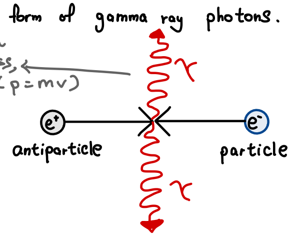
- One electron volt is defined as the energy transferred when an electron is moved through a potential difference of 1 volt.
- Given the rest mass of a particle/antiparticle, its rest energy in MeV can be calculated using $\boxed{E = mc^2}$
- Voltage = Energy/Charge (E/e) $\Rightarrow$ $E = eV$

Annihilation

- Annihilation occurs when a particle and a corresponding antiparticle meet and their mass is converted into EM energy in the form of photons. (mass and energy are equivalent due to $E = mc^2$).
- All the mass of the particle and antiparticle gets converted to energy in the form of gamma ray photons.

How are energy stored in "mass"?

Even though light is massless, it has momentum ($p = mv$)



- Rest energy (energy "stored in mass") = $\boxed{E = mc^2}$ (this equation only applies to resting mass.
- The notation for rest energy is E_0.

Conservation of energy in annihilation

- Energy cannot be created nor destroyed.
- The energy of the two photons, $2hf_{min}$ (derived from equation $E = hf$) should equal to the rest energy of the particle and antiparticle:

$$\boxed{2hf_{min} = 2E_0}$$

↓ factoring

$$\boxed{\text{Minimum energy of each photon produced, } hf_{min} = E_0}$$

rest energy (mc^2)

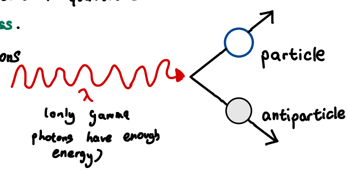
$$\boxed{{}^{0}_{-1}\beta^- + {}^{0}_{+1}\beta^+ \Rightarrow 2\,{}^{0}_{0}\gamma}$$

Use of annihilation

- PET Scans (Positron emitting tomography) work by putting a positron-emitting isotope into the blood, and detecting the gamma rays produced by the electron-positron annihilation that occurs.
- The gamma rays are always produced in pairs moving in opposite directions, so they're easily distinguished by a scintillator. (machine to form an image)

Pair Production

- In pair production, a photon creates a particle and a corresponding antiparticle and vanishes in the process.
- Pair production only happens if there is enough energy to produce the masses of the particles.
- It must always produce a particle and its corresponding antiparticle because certain quantities must be conserved: energy, momentum, baryon number, lepton number, charge, strangeness.
- Pair production can also be used to produce protons by firing two protons with a lot of kinetic energy. Energy is converted to more particles.



Conservation of energy in pair production

- Energy cannot be created nor destroyed.
- One photon must produce a particle-antiparticle pair - the minimum energy being the total rest energy of the particles that are produced.

→ Rest energy of a particle is the amount of energy that would be produced if all of its mass was transformed into energy.

$$\boxed{\text{Minimum energy of photon needed} = hf_{min} = 2E_0}$$

rest energy of particle type produced in MeV (mc^2)

$${}^{0}_{0}\gamma \rightarrow \underbrace{{}^{0}_{-1}\beta + {}^{0}_{+1}\beta}_{2E_0 = 2m_0c^2}$$

E_γ

m_0 → rest mass

$$E_\gamma = 2m_0c^2$$

$$E_\gamma = hf = 2m_0c^2$$

What is a force?

- We know that when a single force acts on an object, it changes the momentum (velocity/mass/energy) of an object.
- Momentum = mass × velocity

- Newton's Third Law: When two objects, they exert equal and opposite forces on each other.
- Momentum is transferred between the objects by these forces, if no other forces act on them.

The Four Forces in Fundamental Interactions

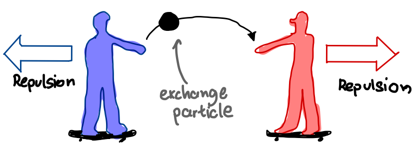
- Gravitational: Affects ALL matter - always attractive
- Strong: Holds the nucleus together. Also known as strong nuclear force / strong interaction. (Read above)
- Weak: Responsible for the radioactive decay of atoms. (Read below)
- Electromagnetic: A type of physical interaction between electrically charged particles. (Attractive / repulsion)

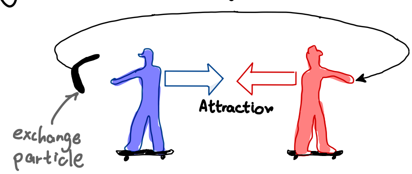
Why do electromagnetic forces (attraction and repulsion) happen?

- American Feynman researched that electromagnetic forces occur due to the exchange of virtual photons.

Interaction Analogy

- Repulsion: Two skaters throwing a ball to each other causes them to repel, as the ball transfers momentum from the thrower to the catcher. The people represent same-charged particles, and the ball represents an "exchange particle".
- Attraction: Two skaters throwing a boomerang to each other causes them to attract. Again, the people represent oppositely charged particles and the boomerang represents an "exchange particle".





The weak nuclear force

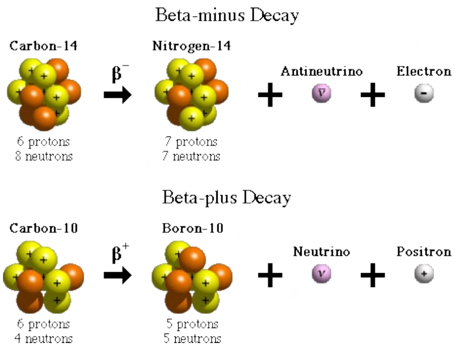
- As mentioned before, the strong nuclear force holds the neutrons and protons in a nucleus together. But it doesn't cause a neutron to change into a proton in β^- decay, or a proton to change into a neutron in β^+ decay.
- The particle conversions cannot be the electromagnetic force as neutron is uncharged.
- Gravity is not the force as well as they don't change particles.
- The strong nuclear force is also not the case for these decay as it involves particles other than hadrons (like electron and anti-neutrino)
- Hence there must be a different force at work causing these particle changes in beta plus/ minus decay.
- This is known as the weak nuclear force.

Why is the weak nuclear force weak?

- The force must be weaker than the strong nuclear force, otherwise it would affect the stable nuclei.

Neutrino / antineutrino interactions

- In both β^- decay and β^+ decay, a new particle and a new antiparticle are created in each type of decay.
- But unlike pair production, a corresponding particle-antiparticle pair is not created — as one is an electron/positron and the other is a neutrino/antineutrino.
- Neutrinos and antineutrinos hardly interact with other particles, but such interactions sometimes happen:
  - → A neutrino can interact with a neutron and make it change into a proton. A β^- particle (an electron) is created and emitted.
  - → An antineutrino can interact with a proton and make it change into a neutron. A β^+ particle (positron) is created and emitted.



Exchange Particles

← also known as Gauge bosons

→ Exchange particles transfers energy, momentum, force and charge. (only happens sometimes)

- Exchange particles are how forces act between two particles. They are virtual particles.
- The electrostatic repulsion between two protons is caused by the exchange of virtual protons, which are the exchange particles of the electromagnetic force.
- Each four fundamental forces (strong, weak, gravity, electromagnetic) has its own exchange particle. These exchange particles are called gauge bosons.

How do exchange particles / Gauge bosons differ from each other?

!!

Fundamental Forces	Gauge bosons (exchange particles)	Particles Affected
Strong	Gluons (pions for quarks)	Quarks → hence hadrons
Electromagnetic	Virtual photon (γ)	Charged particles only
Weak	Z^0, W^+, W^- bosons	All particles → quarks / leptons
Gravitational	Graviton (not observed)	All particles with mass

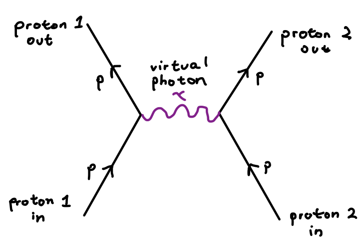
- The size of the exchange particle determines the range of the force.
- Heavier exchange particles have a SHORTER range. $\xrightarrow{\text{hence}}$ the force itself has a shorter range.
- W bosons (weak force exchange particle) have a mass of about 100 times that of a proton, which gives the weak force a very SHORT range. They could be positive (W^+) or negative (W^-) ← non-zero rest mass
- On the other hand, the photon has 0 mass, which gives the electromagnetic force an infinite range.

Feynman Diagrams for Particle Interaction

Rules for Feynman diagrams

- We only need to draw them for the weak interaction and the electromagnetic force (the proton-proton diagram to the right demonstrates the repulsive electromagnetic force.)
- Direction of time points upwards in the diagrams.

Proton - proton repulsion



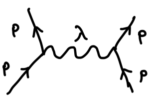
Feynman Diagrams

also known as boson

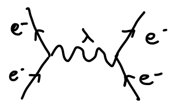
Force	Exchange Particle	Range	Relative Strength	Acts on
Strong	Gluon (pions for quarks)	10^{-15} m	1	Quarks
Electromagnetic	Virtual photon (λ)	∞	10^{-2}	Charged particles
weak	Z^0, W^+, W^- bosons	10^{-17} m	10^{-5}	Quarks and leptons
Gravity	Graviton	∞	10^{-40}	All matter with mass

Electromagnetic force: (boson: virtual photon)

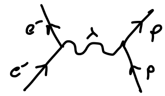
proton-proton



electron-electron

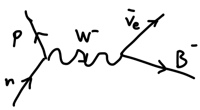


electron-proton

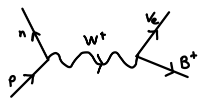


Weak Force: (boson: W^+, W^-)

B⁻ decay (in terms of nucleons)



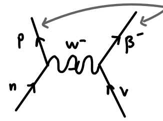
B⁺ decay (in terms of nucleons)

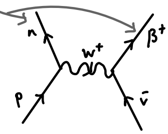


neutron-neutrino

conservation of charge

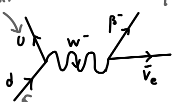
proton-antineutrino





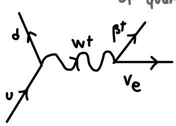
β⁻ decay (in terms of quarks)

proton: uud



neutron: udd

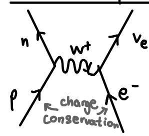
β⁺ decay (in terms of quarks)

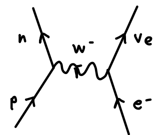


Electron capture

different "acting" particles

electron-proton collision



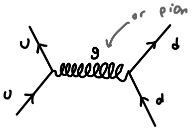


"proton rich" nucleus turns into a neutron as a result of interacting with an inner shell electron

electron requires very high kinetic energy to collide with proton

Strong nuclear force: (boson: gluon)

up quark – down quark attraction



proton: uud
neutron: udd

W-bosons VS photons

Unlike photons, W-bosons:

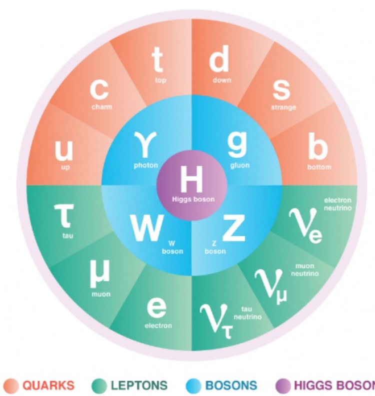
- have a non-zero rest mass
- have a even shorter range than strong force distance
- are positively charged or negatively charged (W^+/ W^-)

Particle Classification

Red = Elementary Particles (Fundamental)

All Particles

- **Fermions** (Half-integer Spin)
  - **Hadrons** (feel the strong force)
    - **Baryons** (3 quarks composition)
      - $\Sigma, \Omega, \Lambda, \Xi$...
      - p, n
        - (uud) (udd)
    - **Mesons** ← do not last long due to annihilation
      (2 quark composition: $q + \bar{q}$)
      - Pions (π^+, π^0, π^-)
      - Kaons (K^+, K^-, K^0)
      - η, B, D...
    - → **Quarks & Antiquarks** (Spin = $\frac{1}{2}$) (Have colour charge)*
      - 1st Gen
        - Up (u)
        - Down (d)
      - 2nd Gen
        - Charm (c)
        - Strange (s)
      - 3rd Gen
        - Top (t)
        - Bottom (b)
  - **Leptons** (does not feel strong force) ↓ (no colour charge) (electroweak interactions)
    - 1st Gen
      - Electron (e^-)
      - Electron neutrino (ν_e)
    - 2nd Gen
      - Muon (μ^-)
      - Muon neutrino (ν_μ)
    - 3rd Gen
      - Tau (τ^-)
      - Tau neutrino (ν_τ)
- **Elementary Bosons** (Integer spin) ← mesons are bosons too but they are not elementary
  - **Gauge bosons** (spin 1) (Exchange particles)
    1. Photon (γ) (electromagnetic interaction)
    2. W and Z bosons (W^+, W^-, Z) (weak interaction)
    3. Eight types of gluons (g) (strong interaction)
    4. Graviton (Theoretical) (Gravity)
  - **Scalar bosons**
    - Higgs boson (H^0)



* Colour charge is related to the exchange of gluons to create a colour field that binds quarks together in hadrons.

Hadrons

- Hadrons are particles that can feel the strong nuclear force. (force that holds the protons together)
- Hadrons are made up of smaller particles called quarks. (hence hadrons are not fundamental particles)
- There are two types of hadrons — baryons and mesons.
- Baryons and mesons are classified according to the number of quarks that make them.

baryons : 3 quarks
mesons : 2 quarks

Baryons

What are baryons? (3 quark composition)

- Protons and neutrons (nucleons) are both baryons
- There are also other baryons that you don't get in normal matter like sigmas (Σ).
- All baryons except a free proton (i.e not in a nucleus) can be unstable.
- This means that all baryons apart from protons decay to become other particles. (eventually a proton)
- Baryons must contain 3 quarks in its composition.

Antiprotons and antineutrons are antibaryons

- Antiparticles are annihilated when they meet the corresponding particle — which means that you don't find antibaryons in ordinary matter.

Conservation of baryon number

- Baryon number is basically nucleon number (if you ignore unusuals like Σ)

Protons/ Neutrons/ Σ :	$B = +1$
Antiprotons/ Antineutrons:	$B = -1$
Non-baryons (mesons/leptons):	$B = 0$

The total baryon number in any particle interaction never changes.

- Using beta-minus decay as an example, we can see the conservation of baryon number come into play here:

$$\underset{B=+1}{n} \longrightarrow \underset{B=+1}{p} + \underbrace{e^- + \bar{\nu}_e}_{B=0}$$

they are leptons

Mesons

What are mesons? (2 quark composition)

- All mesons are unstable.
- Mesons are not observable in day-to-day life. However, large amounts are observable in high-energy particle collisions like in the CERN particle accelerator.

Examples of mesons

- Pions (π^+, π^0, π^-) are the exchange particle of the strong nuclear force.
- π^+ and π^- are particle - antiparticle pairs. They can decay into a muon and an antineutrino.
- Kaons (K^+, K^-, K^0) are heavier and more unstable than pions.
- Kaons have a very short lifetime and can decay into pions, or a muon and an antineutrino.

Leptons and Strange Particles

Leptons

What are leptons?

- Leptons are fundamental particles and they DO NOT feel the strong nuclear force (unlike baryons).
- They interact via the weak interaction and the electromagnetic force if they are charged.
- Leptons, like quarks, come in 3 generations / flavours. (tau - third generation is not in the spec)

lepton collisions produce hadrons

- The universe would be very dull if all its particles were leptons, because:
  - → Neutrinos interact very little.
  - → Taus and muons are very short-lived and decays back to electron.
  - → Electrons repel each other.
- HOWEVER, leptons and antileptons can interact to produce hadrons.
- For example, an electron-positron annihilation event produces a quark and a corresponding antiquark, producing a shower of hadrons in each direction.

Symbol	Relative Charge	L_e	L_μ
e^-	-1	+1	0
ν_e	0	+1	0
μ^-	-1	0	+1
ν_μ	0	0	+1

Generation 1 — Electron & electron neutrino

- Electrons (e^-) are stable leptons.
- Electrons, like other leptons, come with their own neutrino: ν_e.

Generation 2 — Muon & muon neutrino

- Muons (μ^-) are like heavy electrons but they are unstable, and decay eventually into ordinary electrons.

Neutrinos

- Neutrinos travel almost as fast as light, billions of them sweeping through the Earth from space every second with almost no interaction.
- Neutrinos have zero electric charge and almost zero mass. (they have some mass)
- 3 generations of neutrinos: ν_e, ν_μ, ν_τ

Strange Particles

- Strange particles are so called because they have a property called strangeness.
- Strange particles are created via the strong interaction.
- Strangeness is only conserved in the strong interaction.
- Strange particles decay through the weak interaction.
- Strangeness is NOT conserved through the weak interaction.

Quark	Strangeness
s	-1
$\bar{s}$	+1
u	0

Quarks and Antiquarks

What are quarks?

- A quark is a type of elementary particle and a fundamental constituent of matter.
- All commonly observable matter is composed of up quarks, down quarks and electrons.
- Quarks combine to form hadrons and mesons.

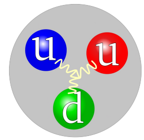
Name	Charge	Baryon number	Strangeness
Up (u)	+2/3	+1/3	0
Down (d)	-1/3	+1/3	0
Strange (s)	-1/3	+1/3	-1

Antimatter for quarks are antiquarks

- Antiparticles of hadrons are made of antiquarks
- Mesons are made with one quark and one antiquark.

Name	Charge	Baryon number	Strangeness
Anti-up ($\bar{u}$)	-2/3	-1/3	0
Anti-down ($\bar{d}$)	+1/3	-1/3	0
Anti-strange ($\bar{s}$)	+1/3	-1/3	+1

Quark Properties



- Types : 6
- Spin : 1/2
- Electric Charge : $\pm \frac{2}{3}$ e
- Baryon number : $\frac{1}{3}$
- Interactions : Electromagnetism, gravitation, strong, weak
- Composition : Elementary Particle

Quark Composition

Proton

$$\underset{+\frac{2}{3}}{u} \quad \underset{+\frac{2}{3}}{u} \quad \underset{-\frac{1}{3}}{d} = +1$$

Neutron

$$\underset{+\frac{2}{3}}{u} \quad \underset{-\frac{1}{3}}{d} \quad \underset{-\frac{1}{3}}{d} = 0$$

Antiproton

$$\underset{-\frac{2}{3}}{\bar{u}} \quad \underset{-\frac{2}{3}}{\bar{u}} \quad \underset{+\frac{1}{3}}{\bar{d}} = -1$$

Antineutron

$$\underset{-\frac{2}{3}}{\bar{u}} \quad \underset{+\frac{1}{3}}{\bar{d}} \quad \underset{+\frac{1}{3}}{\bar{d}} = 0$$

π^+ meson

$$\underset{+\frac{2}{3}}{u} \quad \underset{+\frac{1}{3}}{\bar{d}} = +1$$

π^- meson (antimatter)

$$\underset{-\frac{2}{3}}{\bar{u}} \quad \underset{-\frac{1}{3}}{d} = -1$$

K^+ meson * (K-mesons are strange)

$$\underset{+\frac{2}{3}}{u} \quad \underset{+\frac{1}{3}}{\bar{s}} = +1$$

K^- meson (antimatter)

$$\underset{-\frac{2}{3}}{\bar{u}} \quad \underset{-\frac{1}{3}}{s} = -1$$

K^0 meson (Strangeness: +1)

K^0 and $\bar{K}^0$ has to be memorised →

$$\underset{-\frac{1}{3}}{d} \quad \underset{+\frac{1}{3}}{\bar{s}} = 0$$

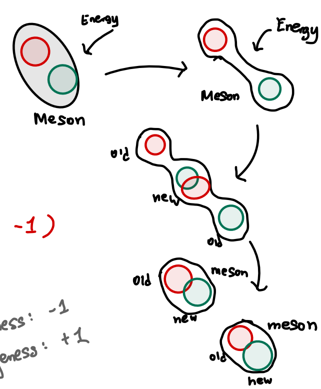
$\bar{K}^0$ meson (antimatter) (Strangeness: -1)

$$\underset{+\frac{1}{3}}{\bar{d}} \quad \underset{-\frac{1}{3}}{s} = 0$$

s-quark strangeness: -1
$\bar{s}$ - quark strangeness: +1

Quark Confinement

- Quark confinement / colour confinement is the phenomenon that colour-charged particles cannot be isolated. (quarks bound by gluons (strong force))
  - Hence it is not possible to isolate a quark
    - Eg. If a proton is blasted with a lot of energy, a single quark would not be removed. The energy supplied would turn into matter due to pair production.



Decays and Conservation Laws

Conservation Laws

· In all particle interactions, energy and momentum are conserved. There are also 4 properties to conserve:
- → Baryon number (B)
- → Charge (Q)
- → Lepton (electron) number (L_e)
- → Lepton (muon) number (L_μ)
- → Strangeness (S) (only conserved in strong interactions)

Decays & Interactions

Proton Collision (Kaon production)

$$p + p \longrightarrow p + p + K^+ + K^-$$

	p	p		p	p	K^+	K^-	
Baryon n. → B:	+1	+1	=	+1	+1	0	0	✓
Charge → Q:	+1	+1	=	+1	+1	+1	−1	✓
Lepton (e) n. → L_e:	0	0	=	0	0	0	0	✓
Lepton (μ) n. → L_μ:	0	0	=	0	0	0	0	✓
Strangeness → S:	0	0	=	0	0	+1	−1	✓

Proton-antiproton Collision (π Production)

$$p + \bar{p} \longrightarrow \pi^+ + \pi^-$$

	p	$\bar{p}$		π^+	π^-	
B:	1	−1	=	0	0	✓
Q:	+1	−1	=	+1	−1	✓
L_e:	0	0	=	0	0	✓
L_μ:	0	0	=	0	0	✓
S:	0	0	=	0	0	✓

π^- Decay

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

	π^-		μ^-	$\bar{\nu}_\mu$	
B:	0	=	0	0	✓
Q:	−1	=	−1	0	✓
L_e:	0	=	0	0	✓
L_μ:	0	=	−1	+1	✓
S:	0	=	0	0	✓

π^+ Decay

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

	π^+		μ^+	ν_μ	
B:	0	=	0	0	✓
Q:	+1	=	+1	0	✓
L_e:	0	=	0	0	✓
L_μ:	0	=	−1	+1	✓
S:	0	=	0	0	✓

μ^- decay

$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

	μ^-		e^-	ν_μ	$\bar{\nu}_e$	
B:	0	=	0	0	0	✓
Q:	−1	=	−1	0	0	✓
L_e:	0	=	1	0	−1	✓
L_μ:	1	=	0	1	0	✓
S:	0	=	0	0	0	✓

μ^+ decay

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

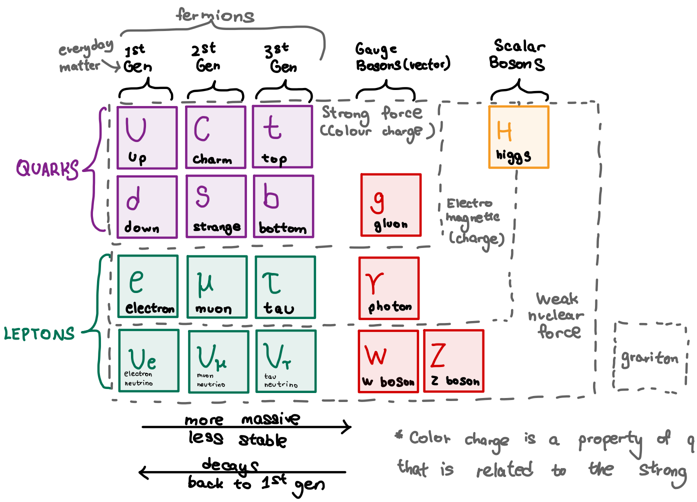
	μ^+		e^+	$\bar{\nu}_\mu$	ν_e	
B:	0	=	0	0	0	✓
Q:	+1	=	+1	0	0	✓
L_e:	0	=	−1	0	+1	✓
L_μ:	−1	=	0	−1	0	✓
S:	0	=	0	0	0	✓

The Standard Model

The Standard Model

· Wiki: The Standard Model of particle physics is the theory describing 3 of the 4 known fundamental forces (gravity is not understood yet) in the universe, as well as classifying all known elementary/fundamental particles.

· To put it simply, the Standard Model shows the smallest "stuff" in the Universe.



* Color charge is a property of quarks and gluons that is related to the strong interaction.

Muons (200× mass of e)

· Muons can be created when cosmic rays strike gas atoms in Earth's atmosphere or in particle accelerators.

Taus (3500× mass of e)

· Tau-particles have a rest mass about 3500 times of an electron.

· They are only observed in particle accelerators.

· The existence of 3 generations are NOT KNOWN as of 2020.

· 2nd and 3rd generation particles are only produced in brief moments and are not seen in everyday life as they decay via the weak force (bosons: W^+, W^-, Z)

· ALL particles above have an antimatter version.

Gluons VS Pions for strong interaction

· The boson (exchange particle) for the strong force is both the gluon and the pion.

· Pions mediate interactions between nucleons (attracts protons together).

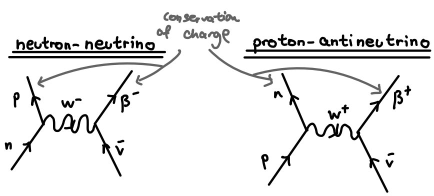
· On the other hand, gluons are responsible for holding quarks together to form hadrons.

· Gluons are fundamental bosons whereas pions are a type of meson which contains a quark and an anti-quark.

Neutrinos' Weak Force Interactions

· Trillions of neutrinos (mostly generated by Sun) fly through us every second.

· Neutrinos barely interact, but if they do, interact with baryons and decay similar to beta decay.



What is the Higg's boson?

· The Higgs boson is the particle associated with the Higgs field, an energy field that gives particles mass. (It gives things mass!!) Ex. Gauge bosons do not interact with Higgs hence do not have mass.