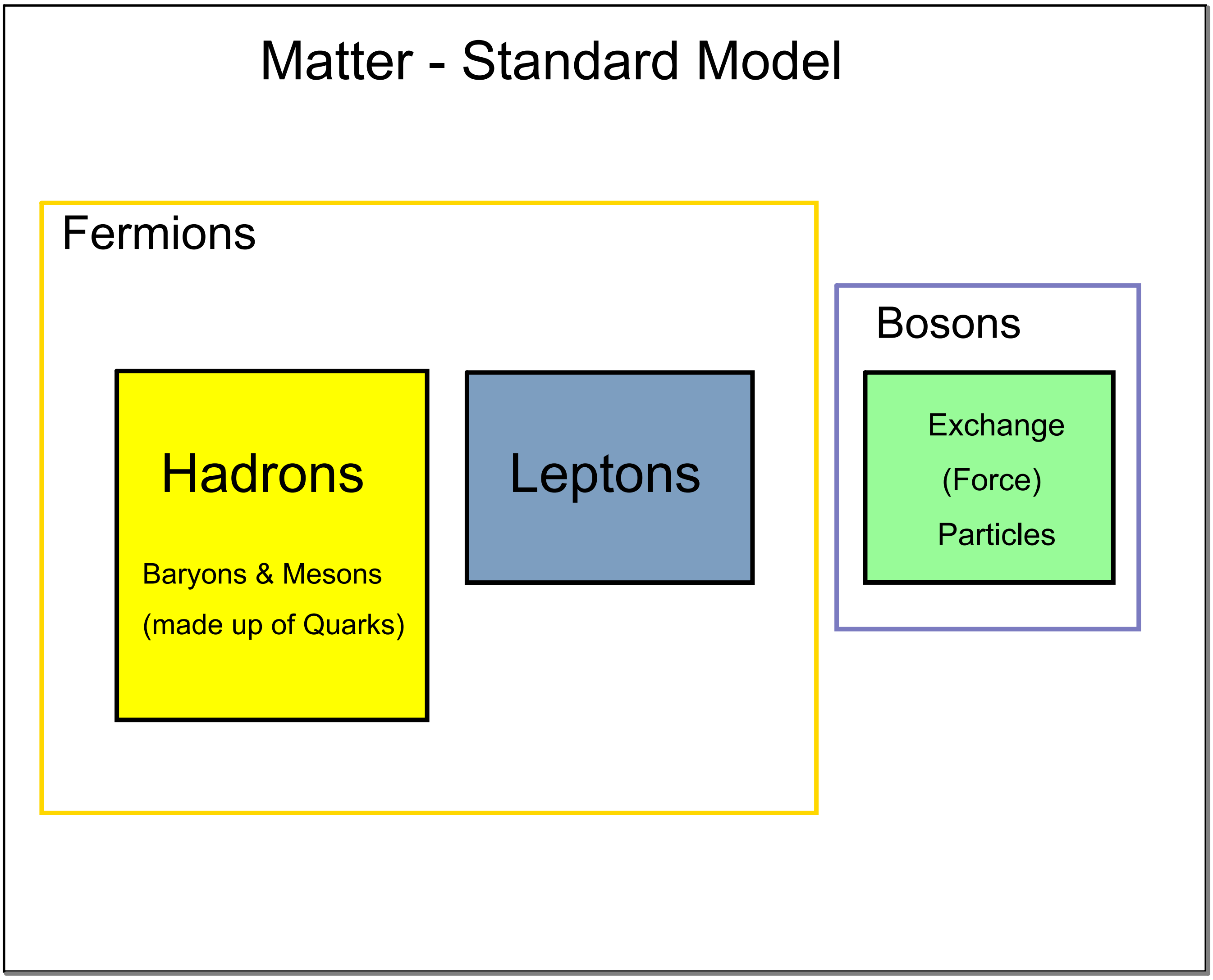

Matter - Standard Model
Fermions
Hadrons
Baryons & Mesons
(made up of Quarks)
Leptons
Bosons
Exchange
(Force)
Particles

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Essential idea: It is believed that all the matter around us is made up of fundamental particles called quarks and leptons. It is known that matter has a hierarchical structure with quarks making up nucleons, nucleons making up nuclei, nuclei and electrons making up atoms and atoms making up molecules. In this hierarchical structure, the smallest scale is seen for quarks and leptons (10^{-18} m).

Topic 7: Atomic, nuclear and particle physics
7.3 – The structure of matter

Understandings:

- Quarks, leptons and their antiparticles
- Hadrons, baryons and mesons
- The conservation laws of charge, baryon number, lepton number and strangeness
- The nature and range of the strong nuclear force, weak nuclear force and electromagnetic force
- Exchange particles
- Feynman diagrams
- Confinement
- The Higgs boson

Applications and skills:

- Describing the Rutherford-Geiger-Marsden experiment that led to the discovery of the nucleus
- Applying conservation laws in particle reactions
- Describing protons and neutrons in terms of quarks
- Comparing the interaction strengths of the fundamental forces, including gravity
- Describing the mediation of the fundamental forces through exchange particles
- Sketching and interpreting simple Feynman diagrams
- Describing why free quarks are not observed

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Guidance:

- A description of the standard model is required

Data booklet reference:

- The quarks

Charge	Quarks			Baryon number
(2/3)e	u	c	t	1/3
-(1/3)e	d	s	b	1/3
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of -1				

Data booklet reference:

- The leptons

Charge	Leptons		
-1e	e	μ	τ
0	ν_e	ν_μ	ν_τ
All leptons have a lepton number of 1 and antileptons have a lepton number of -1			

- The exchange particles

	Gravitational	Weak	Electromagnetic	Strong
Particles experiencing	All	Quarks, leptons	Charged	Quarks, gluons
Particles mediating	Graviton	W^+, W^-, Z^0	γ	Gluons

Structure of Matter

An **elementary particle** is not able to be broken down into smaller components.

ie. the atom used to be an elementary particle, then protons, neutrons, and electrons were discovered.

protons and neutrons were considered elementary until quarks were discovered.

Matter and Anti-Matter

Anti-matter is a form of matter in which each particle has the same mass and an opposite charge (and other numbers) as its counterpart in ordinary matter.

Table 1 Some Properties of Electrons, Protons, Neutrons, and Their Anti-particles

Particle	Symbol	Mass (kg)	Mass (MeV/c^2)	Charge
electron	e^-	9.109×10^{-31}	0.511	−1
positron	e^+	9.109×10^{-31}	0.511	+1
proton	p	1.673×10^{-27}	938	+1
anti-proton	$\bar{p}$	1.673×10^{-27}	938	−1
neutron	n	1.675×10^{-27}	940	0
anti-neutron	$\bar{n}$	1.675×10^{-27}	940	0

$$E = mc^2$$

$$\frac{E}{c^2} = m$$

Topic 7: Atomic, nuclear and particle physics

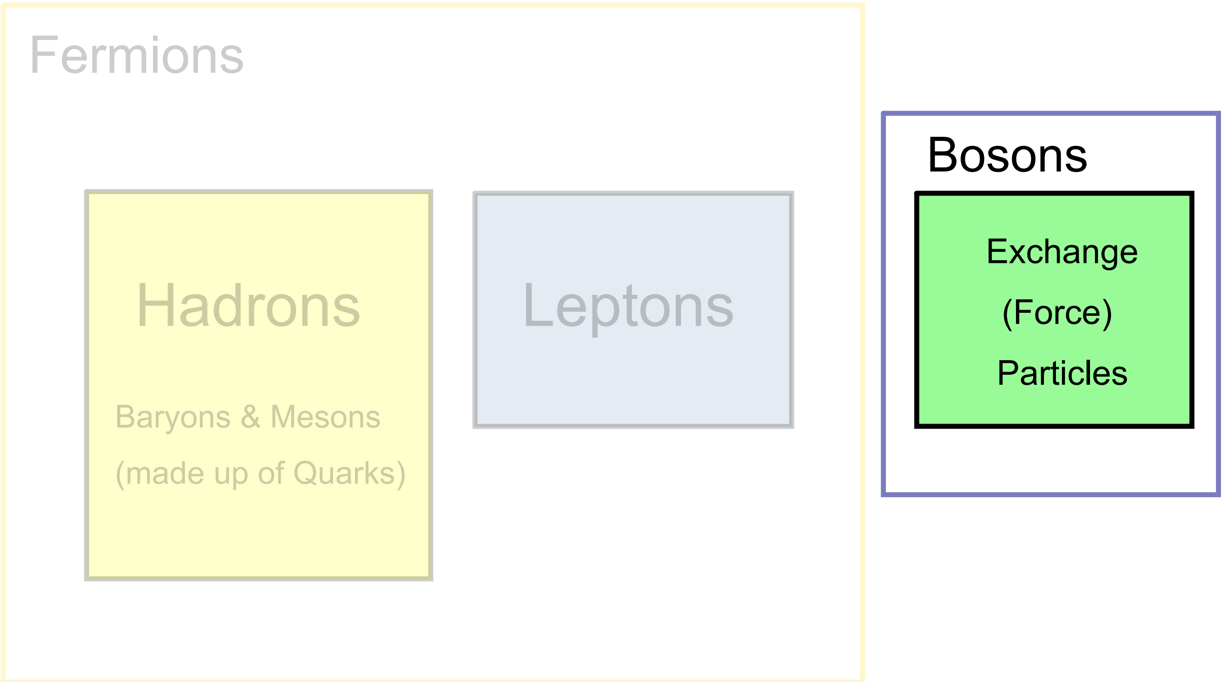
7.3 – The structure of matter

Description and classification of particles

- To date there are three major divisions in the elementary particles.
- The **force carriers** 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.

FYI • For example, quarks interact via the strong force particles called gluons.

Matter - Standard Model



Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

FORCE CARRIERS

The nature and range of the force carriers

- There are four force carriers…
- **INTERACTION 1: STRONG:** 1.0

Strongest of all the interactions between particles. We can give it an arbitrary value of 1.0 for comparison.

- **INTERACTION 2: ELECTROMAGNETIC:** 0.01

This is the NEXT strongest. In comparison to the strong interaction, it has a relative strength of 10^{-2}.

- **INTERACTION 3: WEAK:** 0.000001

This interaction has a relative strength of 10^{-6}.

- **INTERACTION 4: GRAVITATIONAL:**

This interaction has a relative strength of 10^{-39}.
0.000000000000000000000000000000000000001

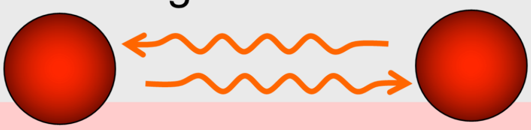
Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

FORCE CARRIERS

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.



FYI

- This photon exchange is the electromagnetic force.

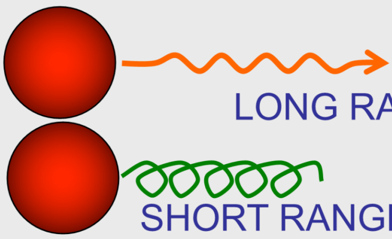
Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

FORCE CARRIERS

The nature and range of the force carriers

- 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

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

The nature and range of the force carriers

FORCE CARRIERS

- Exchange particles whose range of influence is limited are called **virtual particles**.

INTERACTION	RANGE	EXCHANGE PARTICLE	REST MASS
STRONG	10^{-15} m	GLUON g	120 MeV / c^2
Electromagnetic	∞	PHOTON γ	0
WEAK	10^{-18} m	W^+, W^- and Z	80 GeV / c^2
Gravitation	∞	GRAVITON Y	0

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

Please note the range!

Table 7 Bosons, Carriers of Forces, in the Standard Model

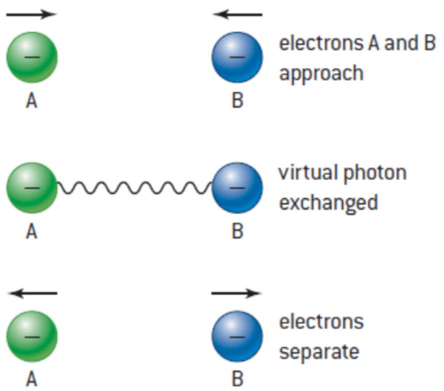
Name	Force
photon	electromagnetic force
W^+, W^-, and Z bosons	weak nuclear force
gluons (eight different types)	strong nuclear force

Force	Exchange particle	Acts on
Gravitational	gravitons (undiscovered)	all particles
Weak nuclear	W^+, W^- and Z^0 bosons	quarks and leptons
Electromagnetic	photons	electrically charged particles
Strong nuclear	gluons (and mesons)	quarks and gluons (and hadrons)

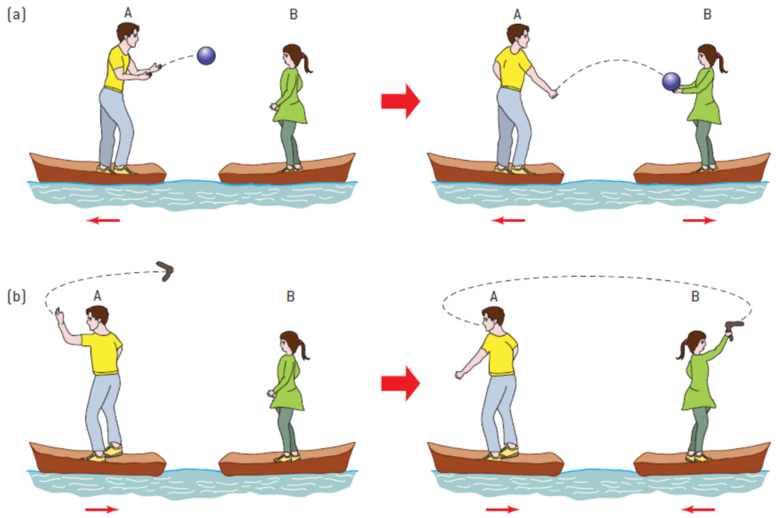
Force	Range	Relative strength	Roles played by these forces in the universe
Gravitational	∞	1	binding planets, solar system, sun, stars, galaxies, clusters of galaxies
Weak nuclear	$\approx 10^{-18}$ m	10^{24}	(W^+, W^-): transmutation of elements (W^0): breaking up of stars (supernovae)
Electromagnetic	∞	10^{35}	binding atoms, creation of magnetic fields
Strong nuclear	$\approx 10^{-15}$ m	10^{37}	binding atomic nuclei, fusion processes in stars

Interaction	Relative strength	Range (m)	Exchange particle	Particles experience
Strong	1	$\sim 10^{-15}$	8 different gluons	Quarks, gluons
Electromagnetic	10^{-2}	infinite	photon	Charged
Weak	10^{-13}	$\sim 10^{-18}$	W^+, W^-, Z^0	Quarks, lepton
Gravity	10^{-39}	infinite	graviton	All

Visualizing an Exchange Particle

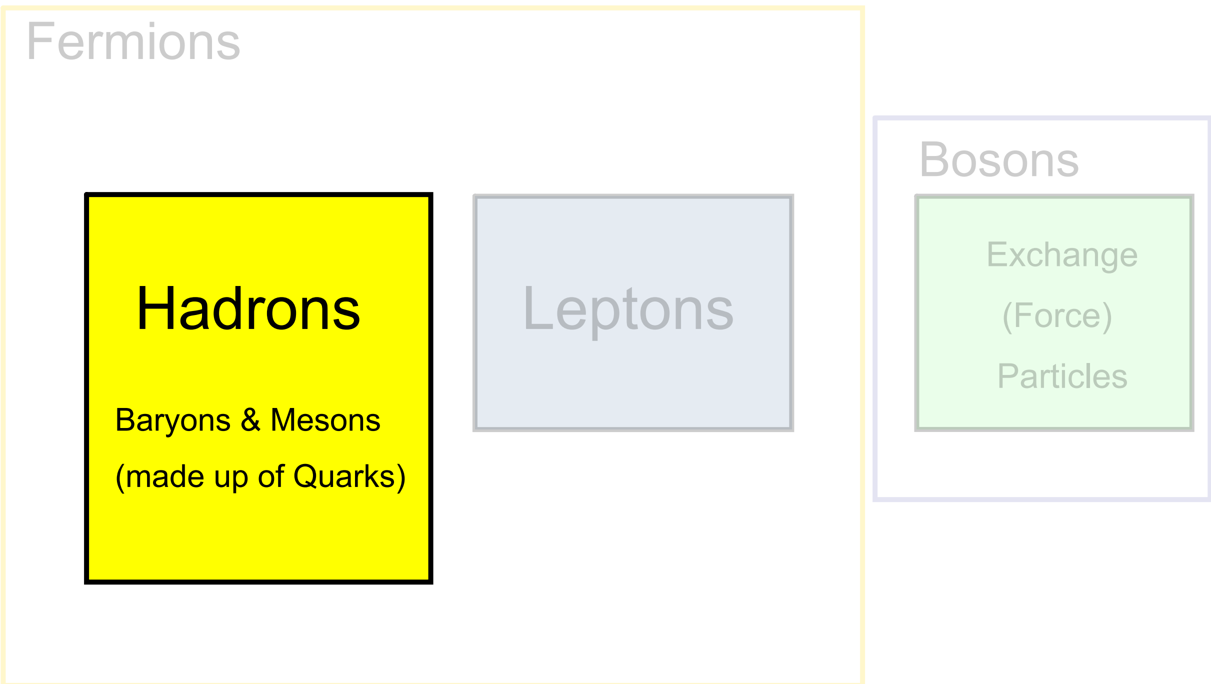


▲ Figure 10 Exchange of virtual photon between two electrons.



▲ Figure 11 Analogy of exchange particles.

Matter - Standard Model



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7.3 – The structure of matter

Quarks and their antiparticles

- Although you have heard of protons and neutrons, both of which react to the strong force exchange particle (the gluon), you have probably *not* heard of most of the following particles:

Particle	Symbol	Particle	Symbol	Particle	Symbol
proton	p	delta	Δ^0	sigma	Σ^+
neutron	n	delta	Δ^-	sigma	Σ^0
lambda	λ^0	delta	Δ^{++}	sigma	Σ^-
omega	Ω^-	delta	Δ^+	xi	Ξ^0

FYI

- With the advent of particle research the list of new particles became endless!

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Quarks and their antiparticles

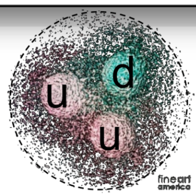
- In 1964 the particle model was looking quite complex and unsatisfying. Murray Gell-Mann proposed a model where all the strong-force particles were made up of three fundamental particles called **quarks**.

Charge	Quarks			Baryon number
$(2/3)e$	u	c	t	1/3
$-(1/3)e$	d	s	b	1/3
All quarks have a strangeness number of 0 except the strange quark that has a strangeness number of -1				

FYI

- A proton is uud and a neutron is udd.

proton



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7.3 – The structure of matter

Quarks and their antiparticles

- 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).
- Thus an antielectron (e^+ or $\bar{e}^-$) has the same mass as an electron but the opposite charge (+1).

$$(i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$$

FYI

- When matter meets antimatter both annihilate each other to become energy!

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Quarks and their antiparticles

- Each quark has an antiquark, which has the opposite charge as the corresponding quark.
- Here are the names of the 6 quarks:

FYI

- An antiquark has the quark symbol, with a bar over it.
- Thus an anti-up quark looks like this: $\bar{u}$.
- An alternate way to represent the anti-up quark would be to write “u-bar.”
- Incidentally, this is how you would actually *say* it.

Table 2 Types of Quarks and Their Properties

Type of quark (flavour)	Symbol	Quark charge (*e*)	Mass	Anti-quark	Anti-quark charge (*e*)
up	u	$+\frac{2}{3}$	1.7 –3.1 MeV	$\bar{u}$	$-\frac{2}{3}$
down	d	$-\frac{1}{3}$	4.1 –5.7 MeV	$\bar{d}$	$+\frac{1}{3}$
charm	c	$+\frac{2}{3}$	1.18 –1.34 GeV	$\bar{c}$	$-\frac{2}{3}$
strange	s	$-\frac{1}{3}$	80 –130 MeV	$\bar{s}$	$+\frac{1}{3}$
top	t	$+\frac{2}{3}$	172.9 GeV	$\bar{t}$	$-\frac{2}{3}$
bottom	b	$-\frac{1}{3}$	4.13–4.37 GeV	$\bar{b}$	$+\frac{1}{3}$

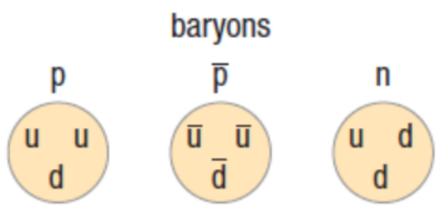


Figure 6 Baryons and anti-baryons are composed of three quarks. The three particles represented here are the proton (p), the anti-proton ($\bar{p}$), and the neutron (n).

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

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.

FYI

- A *single* quark cannot be isolated. We will talk about *quark confinement* later. Basically, confinement states that you cannot separate a single quark from a hadron.

Compare to its individual parts - uud

Table 3 Properties of Some Baryons

Particle	Symbol	Constituent quarks	Lifetime (s)	Mass (MeV/c^2)
proton	p	uud	stable	938
neutron	n	udd	890	940
sigma plus	Σ^+	uus	0.8×10^{-10}	1189
sigma zero	Σ^0	uds	6.0×10^{-20}	1193
sigma minus	Σ^-	dds	1.5×10^{-10}	1197
xi minus	Ξ^-	dss	1.6×10^{-10}	1321

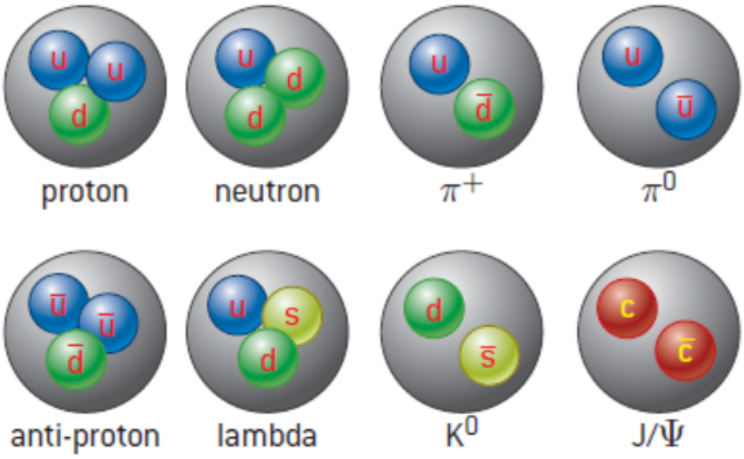
Note: There are many other baryons composed of other combinations of three quarks and anti-quarks.

Table 4 Properties of Some Mesons

Particle	Symbol	Constituent quarks	Lifetime (s)	Mass (MeV/c^2)
pion (pi plus)	π^+	$u\bar{d}$	2.6×10^{-8}	140
pi zero*	π^0	$d\bar{d}/u\bar{u}$	8.4×10^{-17}	135
kaon (K plus)	K^+	$u\bar{s}$	1.2×10^{-8}	494
kaon (K minus)	K^-	$s\bar{u}$	1.2×10^{-8}	494
phi	ϕ	$s\bar{s}$	1.6×10^{-22}	1020

Note: There are many other mesons, which are composed of other combinations of quarks and anti-quarks.

* The π^0 is a quantum-mechanical combination of the $d\bar{d}$ and $u\bar{u}$ quark states.



▲ Figure 6 Three quark and two quark hadrons.

Baryons qqq and antibaryons $\bar{q}\bar{q}\bar{q}$ These are a few of the many types of baryons.			
Symbol	Name	Quark content	Electric charge
p	proton	uud	+1
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	−1
n	neutron	udd	0
Λ	lambda	uds	0
Ω^-	omega	sss	−1

Mesons $q\bar{q}$ These are a few of the many types of mesons.			
Symbol	Name	Quark content	Electric charge
π^+	pion	$u\bar{d}$	+1
K^-	kaon	$s\bar{u}$	−1
ρ^+	rho	$u\bar{d}$	+1
B^0	B-zero	$d\bar{b}$	0
η_c	eta-c	$c\bar{c}$	0

▲ Figure 7 Baryons and mesons.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

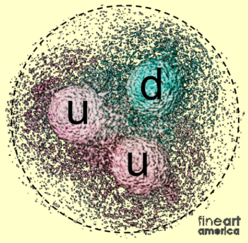
Protons and neutrons in terms of quarks

- 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.

SOLUTION:

- The charge of an up quark is +2/3.
- The charge of a down quark is -1/3.



proton

Thus

Proton = uud : (+2/3) + (+2/3) + (-1/3) = +1.

Neutron = udd : (+2/3) + (-1/3) + (-1/3) = 0.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Conservation of baryon number

- The **baryon number** B of a quark is +1/3. The baryon number of an antiquark is -1/3.

Quark: B = +1/3
Antiquark: B = -1/3

quark (q) or antiquark ($\bar{q}$) baryon number B

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

SOLUTION:

Proton = uud : (+1/3) + (+1/3) + (+1/3) = +1.

Antiproton = $\bar{u}\bar{u}\bar{d}$: (-1/3) + (- 1/3) + (- 1/3) = -1.

A meson has the quark makeup ($q\bar{q}$) so that it has a baryon number of (+1/3) + (-1/3) = 0.

FYI • Like charge, baryon number is conserved in all reactions.

Table 4 Baryon Numbers

Particle	Baryon Number
baryon	+1
antibaryon	−1
mesons	0
leptons	0
gauge bosons	0
quarks	$\frac{1}{3}$
antiquarks	$-\frac{1}{3}$

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Conservation of strangeness

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

S = # antistrange quarks – # strange quarks	strangeness S

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

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

- From the above formula

S = # antistrange quarks – # strange quarks

= 0 – 1 = -1.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Conservation of strangeness

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.

particle	quark structure
K^-	$s\bar{u}$
K^+	$u\bar{s}$
K^0	$d\bar{s}$

(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.

....

....

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Conservation of strangeness

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.

particle	quark structure
K^-	$s\bar{u}$
K^+	$u\bar{s}$
K^0	$d\bar{s}$

(b) State the quark structure of the proton.

- The proton is composed of uud.

....

....

....

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Conservation of strangeness

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.

particle	quark structure
K^-	$s\bar{u}$
K^+	$u\bar{s}$
K^0	$d\bar{s}$

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

- If X is sss, then the reaction can be written

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

- 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.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

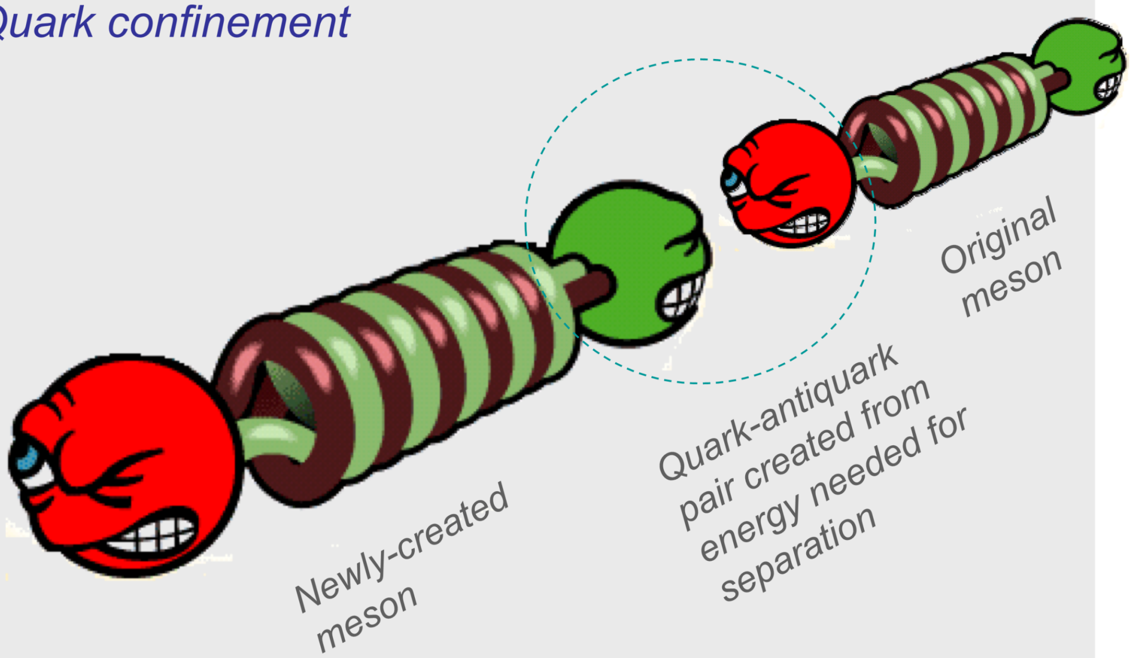
Quark confinement

- 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!

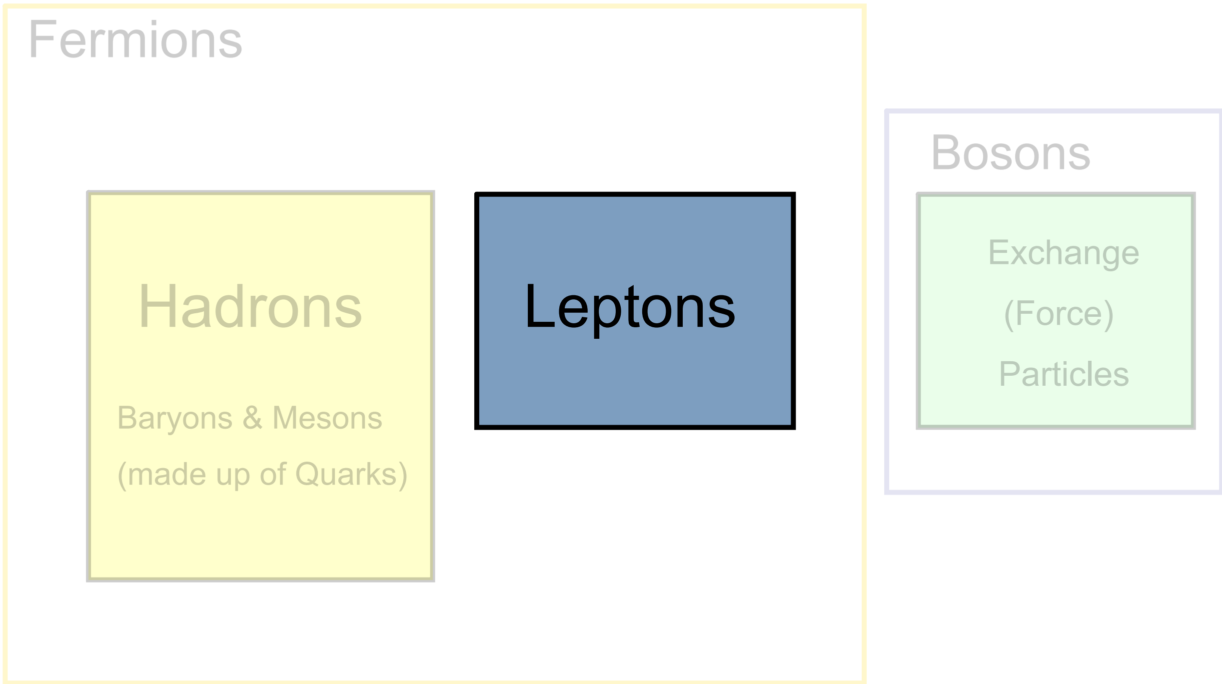
Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Quark confinement



Matter - Standard Model



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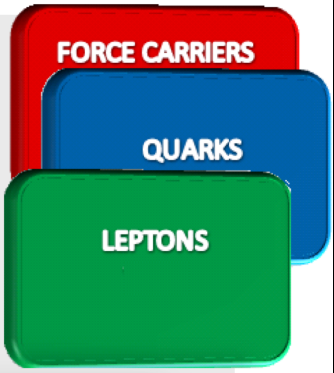
7.3 – The structure of matter

Leptons and their antiparticles



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

Charge	Leptons		
-1*e*	e	μ	τ
0	ν_e	ν_μ	ν_τ

All leptons have a lepton number of 1 and antileptons have a lepton number of -1

FYI

- Of course the leptons also have their antiparticles.

Leptons				Charge/e	Lepton number (L)
Particle	e	μ	τ	−1	+1
Antiparticles	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$	+1	−1
Neutrinos	ν_e	ν_μ	ν_τ	0	+1
Antineutrinos	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	0	−1

Topic 7: Atomic, nuclear and particle physics

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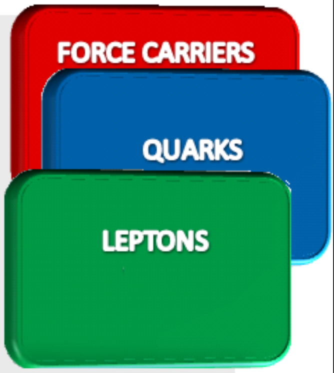


Leptons and their antiparticles

- 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.
- Here are the names of the 6 leptons:

FYI

- Leptons and quarks also react to gravitons.

Table 5 Leptons and Their Properties

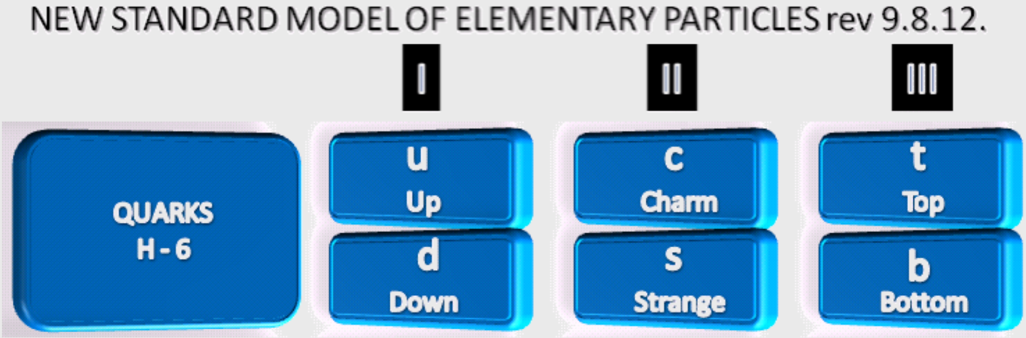
Particle	Symbol	Lepton charge	Mass/c^2	Anti-lepton	Anti-lepton charge
electron	e^-	–1	0.511 MeV	e^+	1
electron neutrino	ν_e	0	0.05 eV < m < 2 eV	$\bar{\nu}_e$	0
muon	μ^-	–1	106 MeV	μ^+	1
muon neutrino	ν_μ	0	< 0.19 MeV	$\bar{\nu}_\mu$	0
tau	τ^-	–1	1780 MeV	τ^+	1
tau neutrino	ν_τ	0	< 18 MeV	$\bar{\nu}_\tau$	0

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

The standard model

- 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.



FYI

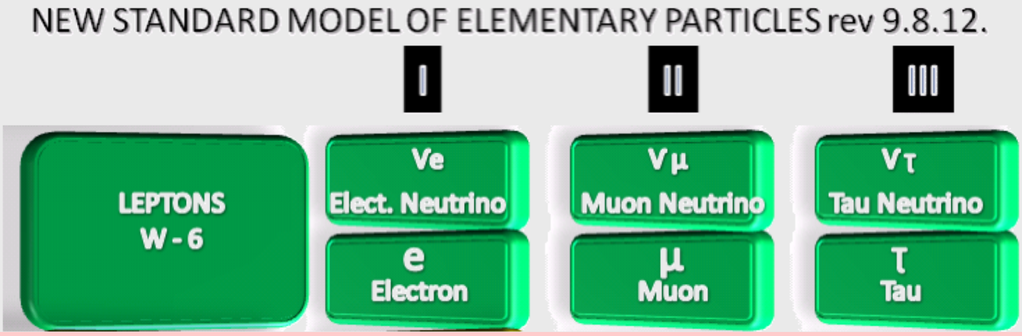
- Particles are divided into “generations” or “families” of increasing mass.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

The standard model

- The following graphic shows part of an organizational structure for particles called the **standard model**.
- These are the leptons, the most common of which is the electron.



FYI

- Muons are created in upper atmosphere by cosmic rays. Tau particles are created in the laboratory.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Leptons and their antiparticles

- Like baryons, leptons also have **lepton numbers**.

Lepton: L = +1 Antilepton: L = -1	lepton and antilepton number L

- Lepton number must be conserved **by generation**.

NEW STANDARD MODEL OF ELEMENTARY PARTICLES rev 9.8.12.

- In any reaction involving leptons, the total number in each generation must remain the same.

Worked examples

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

b) Deduce the quark composition of the uncharged pion.

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:

$uud + \bar{u}d \rightarrow ddu + ??$

$?? = u\bar{u}$ in order to balance this equation.

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 8×10^{-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

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.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

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 $L_I = +1$.
- A positron is an antiparticle and so has $L_I = -1$.
- An antielectron neutrino has $L_I = -1$.
- An antimuon neutrino has $L_{II} = -1$.
- An tau particle has $L_{III} = +1$.
- A proton is not a lepton and so has $L = 0$.

FYI

- Note the family/generation-distinguishing subscripts.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Applying conservation laws in particle reactions

EXAMPLE: Consider the following reactions. Assign charge, lepton numbers and baryon numbers to each particle to determine the feasibility of each reaction.

	$p \rightarrow n + e^{+} + \nu_e$	FEASIBLE
Baryon number:	$1 = 1 + 0 + 0$	
Lepton number:	$0 = 0 + {}^{-}1_{I} + {}^{+}1_{I}$	
Charge:	$1 = 0 + {}^{+}1 + 0$	
	$n \rightarrow p + e^{-} + \bar{\nu}_{\mu}$	NOT FEASIBLE
Baryon number:	$1 = 1 + 0 + 0$	*L* must be conserved by family.
Lepton number:	$0 \neq 0 + {}^{+}1_{I} + {}^{-}1_{II}$	
Charge:	$0 = 1 + {}^{-}1 + 0$	
	$n + p \rightarrow \mu^{+} + \nu_{\mu}$	NOT FEASIBLE
Baryon number:	$1 + 1 \neq 0 + 0$	*B* must be conserved.
Lepton number:	$0 + 0 = {}^{-}1_{II} + 1_{II}$	
Charge:	$0 + 1 = {}^{+}1 + 0$	

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Applying conservation laws in particle reactions

This question is about particle physics.

(a) Possible particle reactions are given below. They **cannot** take place because they violate one or more conservation laws. For each reaction identify **one** conservation law that is violated.

(i) $\mu^- \rightarrow e^- + \gamma$

Conservation law: ....

- *L* must be conserved by family.
- Thus L_{II} and L_I are not conserved.

(ii) $p + n \rightarrow p + \pi^0$

Conservation law: ....

- A pion is a meson and has $B = 0$.
- *p* and *n* each have $B = 1$.
- Baryon number not conserved.

(iii) $p \rightarrow \pi^+ + \pi^-$

Conservation law: ....

- Baryon number not conserved.
- Charge not conserved.

Topic 7: Atomic, nuclear and particle physics

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Applying conservation laws in particle reactions

This question is about particle physics.

(b) State the name of the exchange particle(s) involved in the strong interaction.

• Gluons. ....

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Applying conservation laws in particle reactions

This question is about fundamental particles.

Particle production and annihilation are subject to conservation laws. Two of these laws are conservation of mass-energy and conservation of momentum.

(a) State the names of **three** other conservation laws.

1. •Conservation of charge.
2. •Conservation of baryon number.
3. •Conservation of lepton number (by family).

•*Also* strangeness, parity, isotopic spin, angular momentum.

Topic 7: Atomic, nuclear and particle physics

7.3 – The structure of matter

Applying conservation laws in particle reactions

This question is about fundamental particles.

Particle production and annihilation are subject to conservation laws. Two of these laws are conservation of mass-energy and conservation of momentum.

(b) Free neutrons are unstable. A neutron may decay to become a proton with the emission of an electron. A student represents the decay by the following equation.

$$^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$$

(i) State, by reference to conservation laws, why the student's equation is not correct.

- Family I lepton number is not conserved.

....

- Equation needs Family I lepton with no charge and L = -1. $\bar{\nu}_e$ fits the bill.

(ii) Write down the correct decay equation.

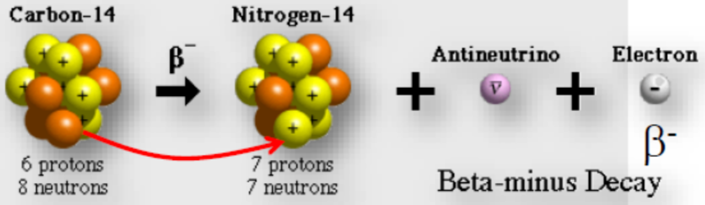
- $n \rightarrow p + e^{-} + \bar{\nu}_e$.

....

Alpha particles, beta particles and gamma rays

- In β^- decay, a neutron becomes a proton and an electron is emitted from the nucleus.

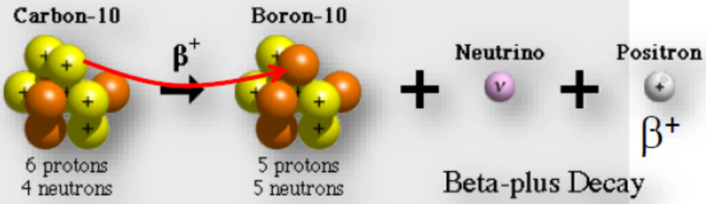
$$^{14}C \rightarrow {}^{14}N + \bar{\nu} + e^-$$



- In β^+ decay, a proton becomes a neutron and a positron is emitted from the nucleus.

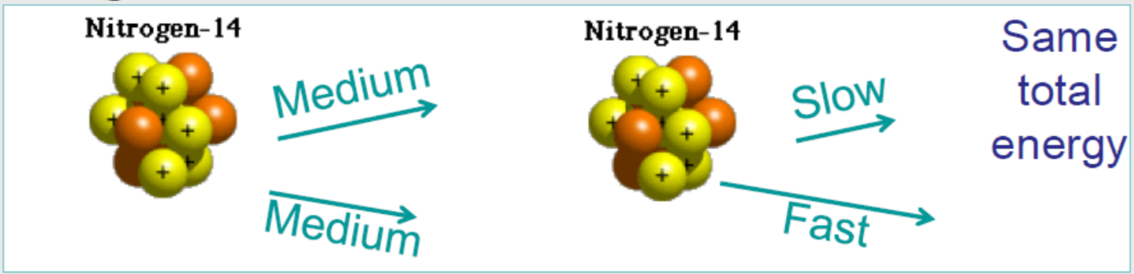
$$^{10}C \rightarrow {}^{10}B + \nu + e^+$$

- In short, a **beta particle** is either an **electron** or it is an **anti-electron**.



Alpha particles, beta particles and gamma rays

•In contrast to the alpha particle, it was discovered that beta particles could have a **large variety of kinetic energies**.



•In order to conserve energy it was postulated that another particle called a **neutrino** ν was created to carry the additional E_K needed to balance the energy.
•Beta (+) decay produces neutrinos ν, while beta (-) decay produces anti-neutrinos $\bar{\nu}$.