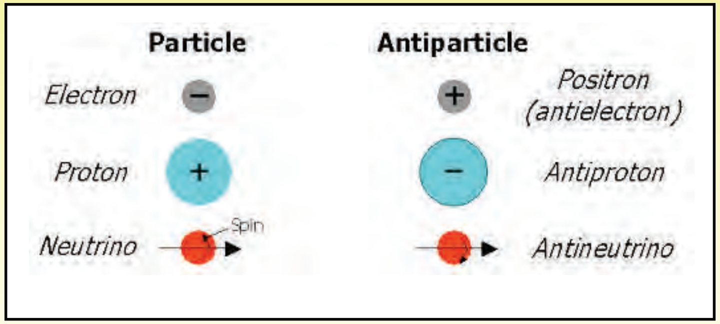
- ***Candidates should be able to* :**
  - *Explain that since **protons** and **neutrons** contain charged constituents called **quarks**, they are therefore, **not fundamental particles.***
  - *Describe the **simple quark model of hadrons** in terms of, **up, down** and **strange** quarks and their respective **antiquarks,** taking into account their **charge, baryon number** and **strangeness.***
  - *Describe how the **quark model** may be extended to include the properties of **charm, topness** and **bottomness.***
  - *Describe the properties of **neutrons** and **protons** in terms of a **simple quark model.***
  - *Describe how there is a **weak interaction** between quarks and that this is responsible for **β-decay.***
  - *State that there are **two types of β-decay.***
  - *Describe the two types of **β-decay in terms of a simple quark model.***
  - *State that **(electron) neutrinos** and **(electron) antineutrinos** are produced during β^+ and β^- decays, respectively.*
  - *State that a β^- **particle is an electron** and a β^+ **particle is a positron.***
  - *State that **electrons** and **neutrinos** are members of a group of particles known as **leptons.***

MATTER AND ANTIMATTER

- Every **particle** has an **antiparticle** (e.g. the **positron** is the antiparticle of the **electron**).

- A particle and its antiparticle have :
  - The **same mass.**
  - **Equal**, but **opposite charge.**
  - **Oppositely directed spin.**

- The diagram below gives some particle-antiparticle examples.



- The existence of antimatter was mathematically predicted by the British physicist **Paul Dirac** in 1928. His equation described a particle which was identical to the electron in every way, except that it was positively charged (i.e. the positron). These positrons were then subsequently discovered by **Carl Anderson** in 1932. **Antiprotons** and **antineutrons** were also first detected as a result of accelerator particle collision experiments in the 1950's and since then antiparticles have been detected for all the known particles. Many antiparticles occur naturally when they are created as a result of cosmic ray collisions with molecules in the atmosphere.

- When a particle meets its antiparticle, they **annihilate** each other and at least **two gamma-ray photons** are produced. **Particle-antiparticle pairs** can also be formed when **very high energy photons of electromagnetic radiation** pass through matter.

- As a result of continued particle accelerator collision experiments, the number of new particles which were being detected was ever-increasing and physicists needed to find some way of grouping them. The particles were grouped or classified according to their **nature** and **interactions***.

*There are four types of **INTERACTION** :

STRONG INTERACTION

This is responsible for the force which holds **nucleons** together. Particles which interact via the strong interaction are called **HADRONS**.

WEAK INTERACTION

This is responsible for the two types of **beta (β)decay** (β^- and β^+) from radioactive nuclei.

ELECTROMAGNETIC INTERACTION

This is responsible for the **electric force between charged particles**.

GRAVITATIONAL INTERACTION

This is responsible for the forces which govern the **motion of planets around stars, moons around planets etc.**.

QUARKS

- The **QUARK MODEL** was independently proposed by the American physicists **Murray Gell-Mann** and **George Zweig** in 1964, as part of an ordering scheme for **hadrons**. The suggestion was that the properties of hadrons, such as the **proton** and **neutron**, could be explained in terms of different combinations of these smaller particles which were to be called **QUARKS**.

WHY THE WEIRD NAME?

*Murray Gell-Mann originally invented the name **QUORK** because he wanted it to have no meaning. This was because meaningful names which had been used in the past for other particles had later turned out to be wrong. For example, the term **ATOM** means **indivisible one** and yet it was found that it could in fact be split into smaller particles! In the end, Gell-Mann took the meaningless term **QUARK** for his suggested fundamental particles from some lines in James Joyce's weird novel, Finnegan's Wake.*

*"...... Three **quarks** for Master Mark*
Sure he hasn't got much of a bark and
Sure any he has it's all beside the mark".

- There was little evidence that quarks actually existed until **1968**, but all six types have since been observed in collision experiments using particle accelerators, with the **TOP (t)** quark being the last to be discovered in **1995**.

In **1969** Murray Gell-Mann was awarded the **Nobel Prize in physics** for his amazing work on elementary particles. The photo opposite shows him receiving the award.

THE QUARK MODEL

- The original model proposed **three quarks** (and their **antiquarks**) which were given the names :

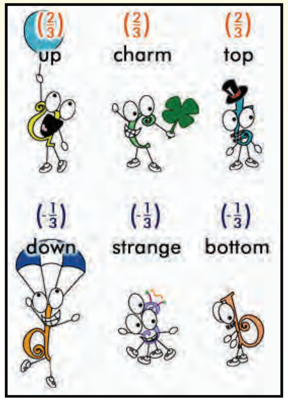
UP u	DOWN d	STRANGE s
ANTIUP $\bar{u}$	ANTIDOWN $\bar{d}$	ANTISTRANGE $\bar{s}$

- As accelerator technology developed and machines capable of delivering ever-increasing energy were set up, the particles produced from collision experiments got **heavier** and could not be accounted for in terms of the **up**, **down** and **strange** quarks.

INCREASING MASS			
	3RD GENERATION	t Top	b Bottom
	2ND GENERATION	c Charm	s Strange
	1ST GENERATION	u Up	d Down

NOTE

- The heavier the quark, the later it was discovered. (charm 1974, bottom 1977, top 1995).
- The **bottom** is sometimes called the **beauty** quark and the **top** is sometimes called the **truth** quark.



THE HADRONS

- **HADRONS** are particles which are made up of **QUARKS**.
- There are two types - **BARYONS** and **MESONS**.
- Although there are many types of hadron only two, **protons** and neutrons, are found in ordinary matter. This is because most hadrons are very unstable and exist only briefly before decaying into other particles. Protons are the only really stable hadrons, since free neutrons (i.e. neutrons outside the nucleus) are found to decay with a half-life of about 15 minutes.

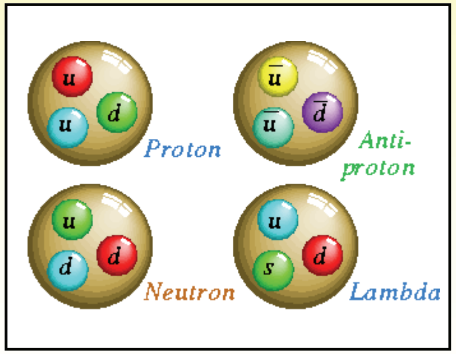
BARYONS

- **BARYONS** are made up of **3 QUARKS** and **ANTIBARYONS** are made up of **3 ANTIQUARKS**.
- **PROTONS** and **NEUTRONS** are the most common examples of baryons.

PROTONS contain **2 UP** quarks and **1 DOWN** quark.
p = uud.

ANTIPROTONS contain **2 ANTIUP** quarks and **1 ANTIDOWN** quark.
$\bar{p} = \bar{u}\bar{u}\bar{d}$.

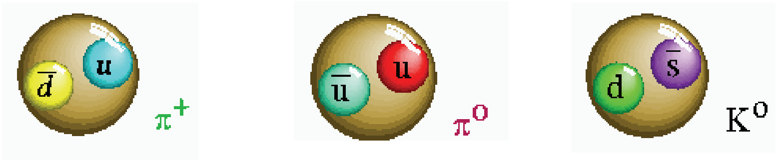
NEUTRONS contain **1 UP** quark and **2 DOWN** quarks.
n = udd



- All baryons are assigned a **BARYON NUMBER (B) of +1 or -1** and **B is conserved** in all particle interactions.

MESONS

- **MESONS** are made up of **1 QUARK** and **1 ANTIQUARK**.
- **PIONS** and **KAONS** are examples of **MESONS**.



π^+ = ud | π^0 = uu | K^0= ds

- All **MESONS** are unstable and rapidly decay into **LEPTONS** and **PHOTONS**.

LEPTONS

- These are truly **FUNDAMENTAL** particles (i.e. particles which are **NOT** made up of smaller particles).
- **LEPTONS** do not feel the strong nuclear force.
- **Leptons** are assigned a **LEPTON NUMBER (L) of +1. Antileptons have L = -1. All other particles have L = 0.**

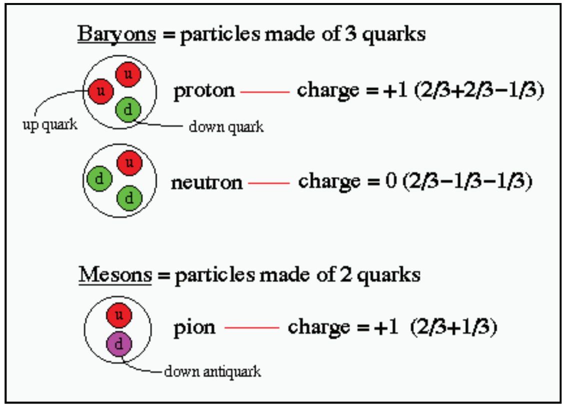
LEPTON NUMBER (L) is conserved in all reactions.

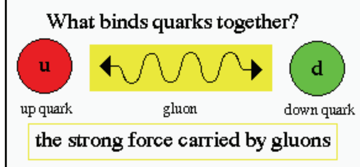
- There are **SIX LEPTONS**, arranged in three generations like the quarks and each lepton has an antiparticle.

3RD GENERATION	τ Tau	ν_τ Tau-neutrino
2ND GENERATION	μ Muon	ν_μ Muon-neutrino
1ST GENERATION	e Electron	ν_e Electron-neutrino

- All ordinary matter is made up of **FIRST GENERATION** particles (i.e. **up quarks**, **down quarks**, **electrons** and **electron-neutrinos**).
- Only the **electron** and the **electron-neutrino** are **stable**. The other leptons decay rapidly into these
- **SECOND** and **THIRD GENERATION** particles are created in accelerator collision experiments and the hot core of stars, but they are **unstable**.

HADRON SUMMARY





QUARK PROPERTIES AND CONSERVATION LAWS

- The table below gives the properties (**charge**, **baryon number** and **strangeness number**) of the six quarks and their antiquarks :

QUARK	SYMBOL	RELATIVE CHARGE(Q)	BARYON NUMBER (B)	STRANGENESS (s)
up	**u**	+2/3	+1/3	0
down	**d**	-1/3	+1/3	0
strange	**s**	-1/3	+1/3	-1
charm	**c**	+2/3	+1/3	0
bottom	**b**	-1/3	+1/3	0
top	**t**	+2/3	+1/3	0
anti-up	**u**	-2/3	-1/3	0
antidown	**d**	+1/3	-1/3	0
antistrange	**s**	+1/3	-1/3	+1
anticharm	**c**	-2/3	-1/3	0
antibottom	**b**	+1/3	-1/3	0
anti-top	**t**	-2/3	-1/3	0

- Each individual quark has a fractional charge and these combine to make up particles having a total relative charge of **0, +1 or -1**.

e.g. **PROTON (uud)** - total charge = +2/3 +2/3 -1/3 = +1.
NEUTRON (udd) - total charge = +2/3 -1/3 -1/3 = 0.
PION, π^+ (ud) - total charge = +2/3 +1/3 = +1.

CHARGE (Q) is always conserved in any particle interaction.

- In order to account for particle interactions which never actually happen (even though mass/energy and charge are conserved), physicists came up with another property which must also be conserved, namely **BARYON NUMBER (B).**

PARTICLE	BARYON NUMBER
ALL baryons	**+1**
ALL antibaryons	**-1**
ALL mesons & leptons	**0**

- All quarks have **B = +1/3** and all antiquarks have **B = -1/3**, from which :

PROTON (uud) - total B = +1/3 +1/3 +1/3 = +1.
NEUTRON (udd) - total B = +1/3 +1/3 +1/3 = +1.
PION, π^+ (ud) - total B= +1/3 -1/3 = 0.

BARYON NUMBER (B) is always conserved in any particle interaction.

- **STRANGENESS** is a property assigned to hadrons to account strange behaviour (e.g. unusually long half-life).

All particles which contain **strange** quarks are called **strange** particles.

All hadrons are given a **STRANGENESS NUMBER (s)** of **+1, 0, -1 or -2.**

STRANGENESS NUMBER (s) is always conserved in hadron interactions.

Consider the two hadron interactions below. Work out if **Q**, **B** and **s** is conserved and hence say if the interaction is possible or not.

1. $p^+ + p^+ \rightarrow p^+ + p^+ + n^0$

Q	
B	
s	

This interaction is **POSSIBLE / NOT POSSIBLE**.

2. $p^+ + p^+ \rightarrow p^+ + p^+ + \pi^- + \pi^+$

Q	
B	
s	

This interaction is **POSSIBLE / NOT POSSIBLE**.

Consider the reaction below. Work out if **Q**, **B** and **L** is conserved and hence say if the reaction is possible or not.

$p^+ + e^- \rightarrow n^0 + \nu_e$

Q	
B	
L	

This interaction is **POSSIBLE / NOT POSSIBLE**.

BETA (β) DECAY

- The **strong interaction** acts between **hadrons** but not between **leptons** and so some particle behaviour cannot be explained in terms of the strong interaction.
- The **WEAK INTERACTION** acts on both **hadrons** and **leptons**.
- The **WEAK INTERACTION** between **quarks** is responsible for **BETA (β) DECAY** and many unstable particles, such as a free neutron, decay as a result of the weak interaction.
- There are two types of **BETA (β) DECAY** :
  - **β^--decay** in which **electrons** are emitted.
  - **β^+-decay** in which **positrons** (electron antiparticles) are emitted.

  Both types of **β-decay** are caused by a weak interaction between the quarks of the neutrons and protons involved.

β^--decay

- **Electrons (β^-, e^-)** can be emitted during the radioactive decay of an unstable nucleus.

  e.g. $^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta^- + {}^{0}_{0}\bar{\nu}_e$

  - In this decay, a **neutron** in the carbon-14 nucleus changes into a **proton** plus an **electron** and an **electron antineutrino**, both of which are emitted.

- Particle equation : $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$
- Quark equation : $udd \rightarrow uud + e^- + \bar{\nu}_e$

Which simplifies to : $d \rightarrow u + e^- + \bar{\nu}_e$

APPLYING CONSERVATION LAWS

Simplified quark equation for β^--decay : $d \rightarrow u + e^- + \nu_e$

- Conservation of **mass/energy** and **momentum** is satisfied by the k.e. of the emitted particles.
- Conservation of **charge (Q)** : $-1/3 \rightarrow +2/3 + -1 + 0$
- Conservation of **baryon number (B)** : $1/3 \rightarrow 1/3 + 0 + 0$
- Conservation of **lepton number (L)** : $0 \rightarrow 0 + +1 + -1$

β^+-decay

- **Positrons (β^+, e^+)** can be emitted during the radioactive decay of an unstable nucleus.

e.g. $^{30}_{15}Po \rightarrow {}^{30}_{14}Si + {}^{0}_{+1}\beta^+ + {}^{0}_{0}\nu_e$

- In this decay, a **proton** in the polonium-15 nucleus changes into a **neutron** plus a **positron** and an **electron neutrino**, both of which are emitted.

- Particle equation : $p^+ \rightarrow n^0 + e^+ + \nu_e$
- Quark equation : $uud \rightarrow udd + e^+ + \nu_e$

Which simplifies to : $u \rightarrow d + e^+ + \nu_e$

APPLYING CONSERVATION LAWS

Simplified quark equation for β^+-decay : $u \rightarrow d + e^+ + \nu_e$

- Conservation of **mass/energy** and **momentum** is satisfied by the k.e. of the emitted particles.
- Conservation of **charge (Q)** : $2/3 \rightarrow -1/3 + +1 + 0$
- Conservation of **baryon number (B)** : $1/3 \rightarrow 1/3 + 0 + 0$
- Conservation of **lepton number (L)** : $0 \rightarrow 0 + -1 + +1$

PRACTICE QUESTIONS

1 **(a)** State the names of the classes of particles (one in each case) which include :

(i) Positrons and **neutrinos**. **(ii) Protons** and **neutrons**.

(b) An unstable nucleus may decay by emitting a positron and a neutrino. This can be due to a proton decaying to a neutron. **Write an equation** to represent this proton decay.

(c) (i) State the composition of the **proton** and **neutron** in terms of their constituent **quarks**.

(ii) Hence **write an equation** for the process described in (b), in terms of **changes in quark composition**.

(iii) State the **baryon number** and **charge** of each particle in the equation of **(c) (ii)**. Hence show that baryon number and charge are **conserved**.

(OCR A2 Physics - Module 2825/04 - Pre 2004)

2 **(a)** State the names of **two** classes of particle, each of which includes both the **proton** and the **neutron.**

(b) It is thought that, in certain circumstances, the **proton** has a slight probability of decaying into a **neutron,** a **positron** and a **third particle.**

- **Write an equation** to represent this reaction.
- State the name of the **third particle**.

(c) A **free neutron** is known to decay with a half-life of about 10 minutes. In what situation are both **neutrons** and **protons stable?**

(d) **(i)** State the **quark** composition of the **proton** and the **neutron.**

(ii) In the reaction $p^+ + p^+ \rightarrow p^+ + n^0 + \pi^+$ two quarks are created.

These are a **down quark (d)** and an **anti-down quark ($\bar{d}$).** Simplify this equation and using your answers to **(d) (i), write a quark equation.**

(iii) Hence deduce the **quark** composition of the **π^+ particle.**

(OCR A2 Physics - Module 2825/04 - June 2004)

3 This question is about the properties of **baryons** and **leptons.**

(a) Choose **two** examples of **baryons** and for each example discuss :

- Their **composition.**
- Their **stability.**

(a) Choose **two** examples of **leptons** and for each example discuss :

- Their **composition.**
- The **forces** which affect them
- **Where** they may be found.

(OCR A2 Physics - Module 2825/04 - June 2004)

1 **(a)** There are **six quarks.** Name them.

(b) State the **quark composition** of a **proton** and a **neutron.**

(c) **(i)** Distinguish between the **two** types of **β-decay.**

(ii) Nitrogen-14 can be formed as a result of two β-decay reactions. $^{14}_{7}N$

- β-decay of **carbon-14** $^{14}_{6}C$
- β-decay of **oxygen-14** $^{14}_{8}O$

Write nuclear equations for these two reactions.

(iii) In each of the reactions in **(ii),** state the **name of the other particle** which is produced.

(iv) Show that the **first** reaction in part **(ii)** is equivalent to the decay of a **neutron into a proton and an electron.**

(v) Describe the decay reaction referred to in part **(iv) in terms of quarks.**

(OCR A2 Physics - Module 2825/04 - Pre 2004)

2 **(a)** **(i)** Name the group of particles of which the **electron** and the **positron** are members.

(ii) Name another member of this group.

(b) **(i)** State the **quark composition** of the **neutron.**

(ii) Complete the table to show the **charge (Q), baryon number (B)** and **strangeness (S)** for the quarks in a **neutron.**

QUARK	Q	B	S

(iii) Hence deduce the values of **Q**, **B** and **S** for the **neutron**.

(c) It is suggested that a **proton** p^+ can react with a **pi particle** π^- to form a **kaon** K^0 and a **neutron** n^0, thus :

$$p^+ + \pi^- \longrightarrow K^0 + n^0$$

Given the data shown in the table below, deduce whether the reaction is possible.

PARTICLE	QUARK COMPOSITION
π-	u d
K^0	d s

(OCR A2 Physics - Module 2825/04 - June 2007)

3 **(a)** State the name of the group of particles which includes both the **proton** and the **neutron**.

(b) Describe the **stability of the proton** : **(i)** When it is **part of a nucleus**.

(ii) When it is **free**.

(c) A group of **500** neutrons are emitted simultaneously in a nuclear reaction and travel through space. Calculate how many of these neutrons will **not** have decayed after **200 s**. (Data : **half-life of a free neutron = 613 s**).

(d) **(i)** Complete the table below to show the **charges** and **baryon numbers** for the **down quark** and the **neutron**.

	CHARGE	BARYON NUMBER
up quark	2/3	1/3
down quark		
neutron		

(ii) By considering the quark composition of the **neutron**, write **two numerical** equations to show how the **charge** and **baryon number** of the neutron are related to the **charge** and **baryon number** of its constituent quarks.

(OCR A2 Physics - Module 2825/04 - June 2008)

4 **(a)** Describe briefly the **quark model of hadrons.**

- Illustrate your answer by referring to the **composition of one hadron.**
- Include in your answer the names of **all the known quarks.**
- Give as much information as you can about **one particular quark.**

(b) A **proton** (p^+) can interact with a π^- **particle** according to the equation :

$$p^+ + \pi^- \longrightarrow n^0 + \pi^0 + \pi^- + X$$

The **charge**, **baryon number** and **strangeness** of the π^- and π^0 **particles** are shown in the table below :

	CHARGE	BARYON NUMBER	STRANGENESS
π^-	-1	0	0
π^0	0	0	0

(i) Assuming that **strangeness is conserved** in this reaction, find the **charge**, **baryon number** and **strangeness** of **particle X**.

(ii) Suggest what **particle X** is.

(OCR A2 Physics - Module 2825/04 - June 2006)