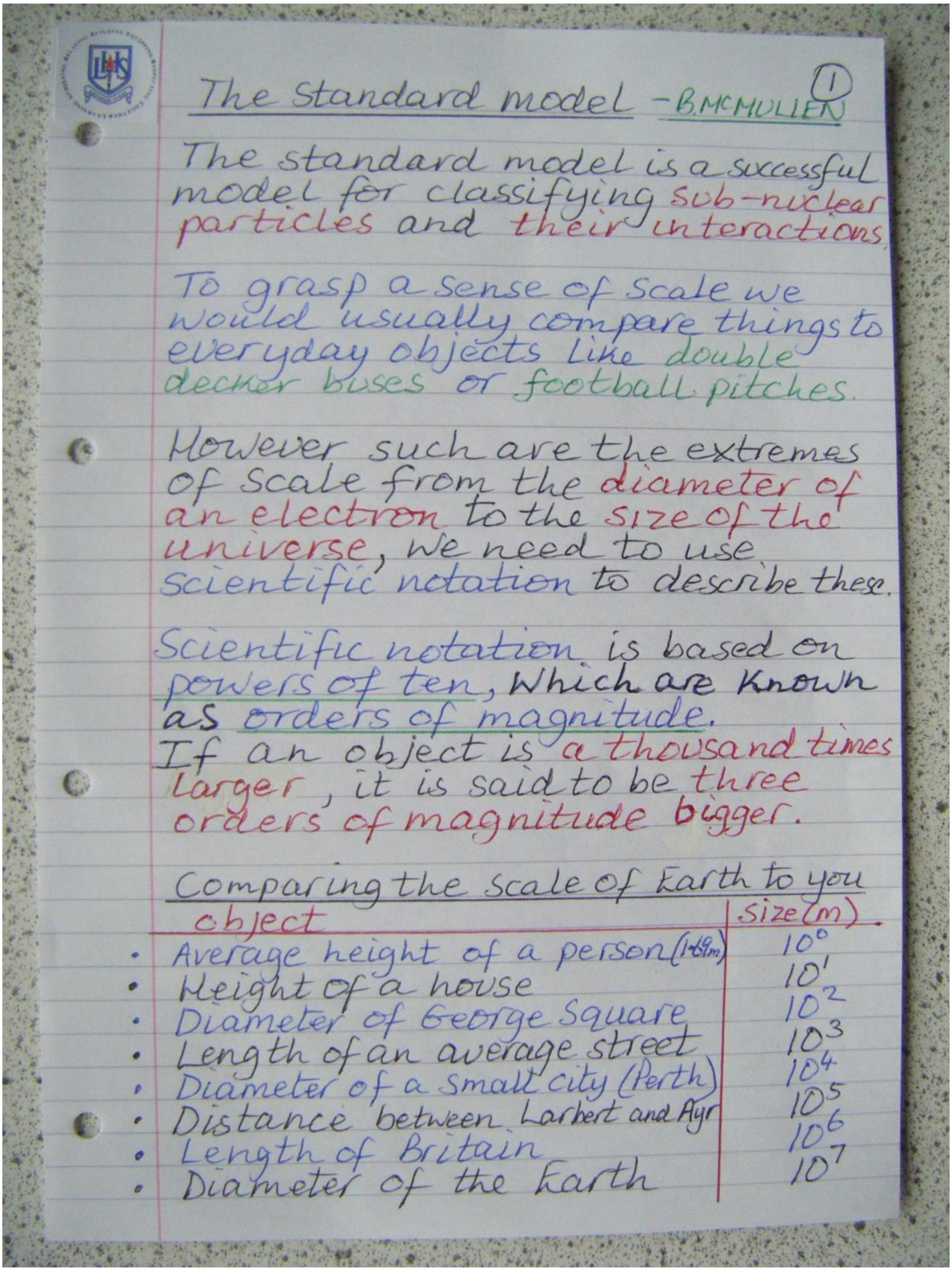


The Standard model - B.McMULLEN

①

The standard model is a successful model for classifying sub-nuclear particles and their interactions.

To grasp a sense of scale we would usually compare things to everyday objects like double decker buses or football pitches.

However such are the extremes of scale from the diameter of an electron to the size of the universe, we need to use scientific notation to describe these.

Scientific notation is based on powers of ten, Which are Known as orders of magnitude.
If an object is a thousand times larger, it is said to be three orders of magnitude bigger.

Comparing the scale of Earth to you

object	size (m).
• Average height of a person (1.69m)	10^0
• Height of a house	10^1
• Diameter of George Square	10^2
• Length of an average street	10^3
• Diameter of a small city (Perth)	10^4
• Distance between Larbert and Ayr	10^5
• Length of Britain	10^6
• Diameter of the Earth	10^7

Q How many orders of magnitude is the Earth bigger than you?

A $\underline{\underline{7}}$ ie $\frac{10^7}{10^0} = \frac{10^7}{1} = \underline{\underline{10^7}}$

Orders of magnitude are used to compare sizes of things such as distance, time and mass.

Examples of distances in metres

object	distance(m)
Diameter of an electron	10^{-18}
Diameter of a proton/neutron	10^{-15}
Typical nucleus diameter	10^{-14}
Typical atom diameter	10^{-10}
Red blood cell	10^{-5}
Human hair	10^{-4}
Human scale	10^{-3} to 10^{2}
Diameter of the sun	10^{9}
Distance to the edge of Solar System	10^{13}
Distance to the furthest known celestial object	10^{26}

Examples of time in seconds

Time Scale	time(s)
Time for photon to cross nucleus	10^{-22}
Time we can measure without technology	$10^{0} \sim 10^{2}$
Time since the Big Bang occured	10^{17}

Examples of mass in kilograms

Object	mass (kg)
mass of an electron	10^{-31}
mass of a proton/neutron	10^{-27}
Typical human mass range	$10^{0} \sim 10^{2}$
Most massive known star (R136a1)	10^{32}
Estimated mass of Universe	$10^{50} \sim 10^{60}$

The Standard Model

In the 1970's the theory of fundamental particles and how they interact was given the name standard model.

This incorporated all that was known about sub-atomic particles at the time and predicted the existence of additional particles.

Kinetic Energy of particles

When a particle is emitted from an atom it will have kinetic energy. This will allow the particle to move away from the atom with a speed v. The speed of the particle will vary depending on the particle involved.

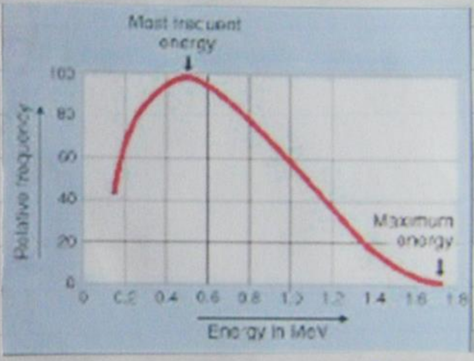
Particles involved with alpha emission

The particles will all have the same kinetic energy and this is determined by the radioactive isotope.

Particles involved with Beta emission

These particles emitted have a wide range of energies. This is shown in the graph below.

most frequent energy from the graph = 0·5MeV



When the beta particle was being emitted a second particle was found to emit at the same time. This particle had a very small mass and no charge and it was named the neutrino.

This second particle emitted was not detected during early experimentation, but was later confirmed as an anti-matter particle.

It was later confirmed as an uncharged anti-electron neutrino.

What is anti-matter?

There are two types of matter:

- matter
- anti-matter

Anti-matter and matter are the same in everything expect they have the opposite charge to each other.

eg matter → Electron
anti-matter → positron

matter and anti-matter cannot co-exist close to each other. If they collided they would annihilate each other.

Quarks

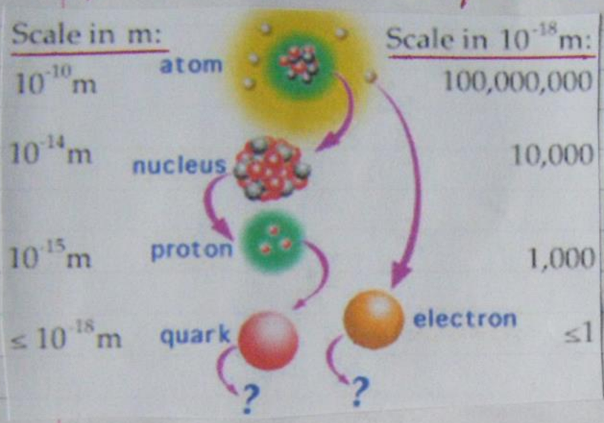
Protons and neutrons in the nucleus of an atom are known as nucleons.

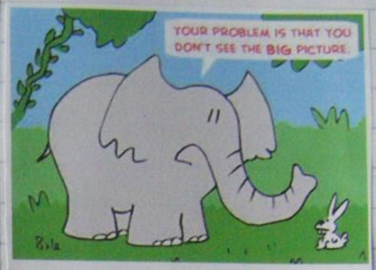
Nucleons are made up of smaller particles called quarks.

There are three generations of quarks, each with two types.

In each generation of quark there is an increase in the mass.

Quarks are believed to be the most fundamental particles.





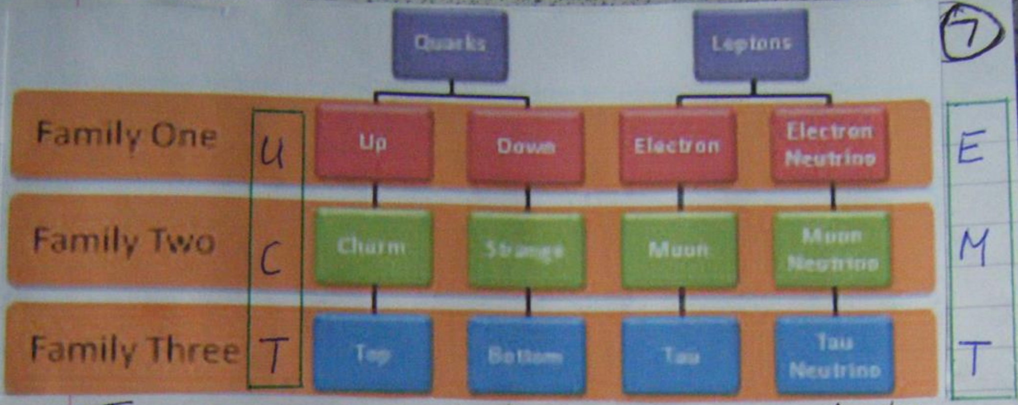
There are other particles that sit alongside quarks called leptons. Lepton comes from the Greek word for light.

Quarks and leptons exist in pairs.

Leptons pairs consist of a charged particle and a neutrino. These have a much smaller mass than their quark counterparts.

There are three generations of these particles with each containing four particles, one pair of quarks and one pair of leptons.

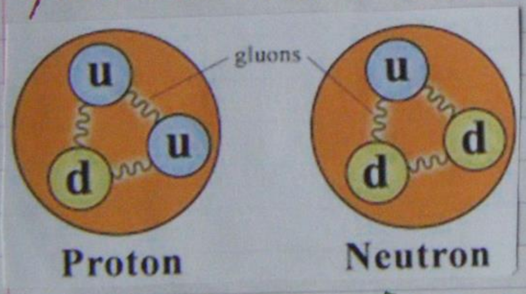
The first family(generation) has the smallest mass and the third family (generation) the largest mass.



		Quarks		Leptons		
Family One	U	Up	Down	Electron	Electron Neutrino	E
Family Two	C	Charm	Strange	Muon	Muon Neutrino	M
Family Three	T	Top	Bottom	Tau	Tau Neutrino	T

In our Universe's low energy state the first family (generation) of particles are the only ones that can exist for any period of time. All of the other particles are short lived.

It involves combinations of first generation quarks that make up protons and neutrons.



Charge on the proton
$= 2(2/3) + (-1/3)$
$= 1$

Charge on a neutron
$= 2/3 + (-1/3-1/3)$
$= 0$

Protons consist of 2 up quarks and one down quark.

Neutrons consist of 1 up quark and 2 down quarks.

*(Up quark charge $= +\frac{2}{3}e$
down quark charge $= -\frac{1}{3}e$)*

Quarks	Charge		Leptons	charge
Up	$+2/3e$	1st	electron	$-e$
down	$-\frac{1}{3}e$		electron neutrino	0
Charm	$+\frac{2}{3}e$	2nd	muon	$-e$
Strange	$-\frac{1}{3}e$		muon neutrino	0
Top	$+\frac{2}{3}e$	3Rd	tau	$-e$
bottom	$-\frac{1}{3}e$		tau neutrino	0

* All of the quarks and leptons have anti-matter equivalents. Each are identical in every way except they have the opposite charge.*

What does this cartoon mean in relation to matter?

FUTURAMA!!

Hadrons

These are combinations of quarks which form new particles.

The term hadron comes from the Greek word 'heavy'.

Hadrons follow simple rules:

- Pairs of quarks combine to form particles called mesons.
- Triplets of quarks combine to form particles called Baryons.
- The electrical charge must have an integral number.
- Only pairs or triplets of quarks may be used.
- Mesons are short-lived particles that are made from matter/Anti-matter combinations.
- Baryons are stable, long lived particles. These can be made from three matter particles or three anti-matter particles.

The Hadron Collider at CERN in Switzerland.

Summary of matter and anti-matter quarks and leptons.

1st family (generation)

Matter

name	Symbol	charge
up	u	$+\frac{2}{3}e$
down	d	$-\frac{1}{3}e$
Electron	e	$-e$
Electron neutrino	ν_e	0

Anti-matter

name	Symbol	charge
anti-up	$\bar{u}$	$-\frac{2}{3}e$
anti-down	$\bar{d}$	$+\frac{1}{3}e$
positron	$\bar{e}$	$+e$
anti-electron neutrino	$\bar{\nu}_e$	0

2nd family (generation)

Matter

name	Symbol	charge
Charm	c	$+\frac{2}{3}e$
Strange	s	$-\frac{1}{3}e$
muon	μ	$-e$
muon neutrino	ν_μ	0

Anti-matter

name	symbol	charge
anti-charm	$\bar{c}$	$-\frac{2}{3}e$
anti-strange	$\bar{s}$	$+\frac{1}{3}e$
anti-muon	$\bar{\mu}$	$+e$
anti-muon neutrino	$\bar{\nu}_\mu$	0

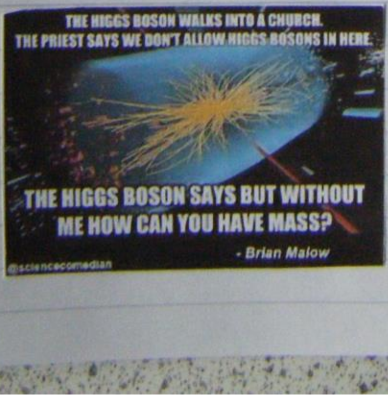
3rd family (generation)

Matter

name	Symbol	charge
top	t	$+\frac{2}{3}e$
bottom	b	$-\frac{1}{3}e$
tau	τ	$-e$
tau neutrino	ν_t	0

Anti-matter

name	Symbol	charge
anti-top	$\bar{t}$	$-\frac{2}{3}e$
anti-bottom	$\bar{b}$	$+\frac{1}{3}e$
anti-tau	$\bar{\tau}$	$+e$
anti-tau neutrino	$\bar{\nu}_\tau$	0



THE HIGGS BOSON WALKS INTO A CHURCH.
THE PRIEST SAYS WE DON'T ALLOW HIGGS BOSONS IN HERE.

THE HIGGS BOSON SAYS BUT WITHOUT ME HOW CAN YOU HAVE MASS?

- Brian Malow

@sciencecomedian

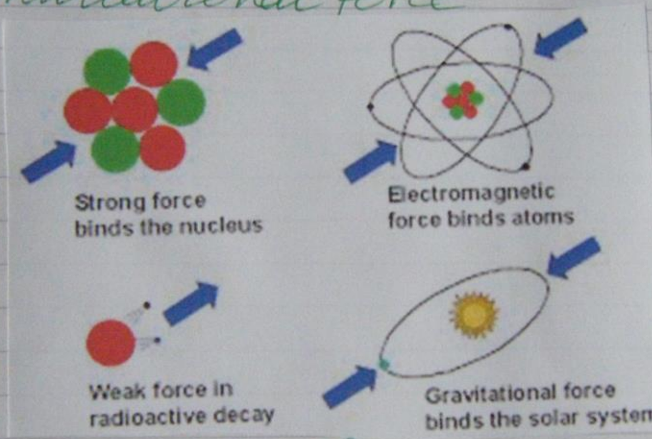
Do you get it?

Particle Interaction

There are four fundamental non-contact forces in the standard model.

These forces explain how matter interacts.

- Strong nuclear force
- Electromagnetic force
- Weak nuclear force
- Gravitational force



- Strong nuclear force

This force holds the nucleus together. This is the only force experienced by quarks. Mesons and baryons that are made up of these quarks including protons. ie hadrons.

- Electromagnetic force

This is weaker than the strong nuclear force. As this force binds atoms together all matter would be easily broken apart without it. This means that the Universe would not exist as we know it.

- Weak nuclear force

This is involved in beta decay and is highly experienced by leptons.

In beta decay a neutron will decay producing a proton, an electron and an anti-neutrino (plural).

neutron → proton + electron + anti-neutrino

ie $^1_0n \rightarrow {}^1_1p + {}^0_{-1}e +$ anti-neutrinos

- Gravitational force

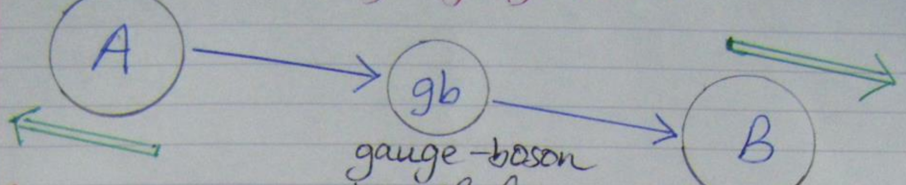
This has by far the smallest magnitude of the four fundamental forces of nature. Large planets give you an idea of the masses required to give a significant value.

These four fundamental forces of nature can be explained by force-mediating particles.

The force acting on one object by another is due to the transfer of particles, between other more massive particles. These particles belong to a group called Bosons.

The force-mediating particles are called gauge-bosons. They carry momentum and energy between massive particles. The transfer of this particle allows a force to be exerted with no contact between the massive particles.

gb–gauge-boson



gauge-boson transfer from A to B.

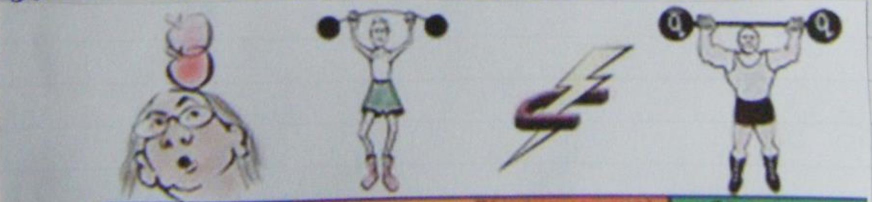
A moves away from B.

B moves away from A.

- Particle A emits a gauge-boson
- Particle A recoils
- Particle B will absorb the gauge-boson.
- Particle B will now move away from particle A.

* This can be thought about in terms of a gun firing a bullet.
The gun will recoil.
The bullet moves away from the gun.
* The bullet hits its target moving it forwards.

The exchange particles that allows the fundamental forces to be exerted are shown in the table below.

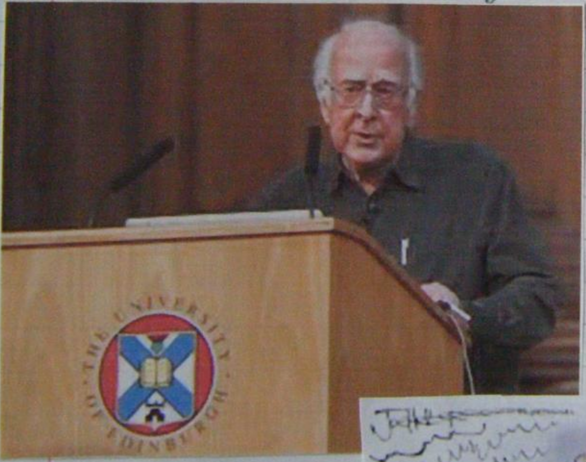


	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

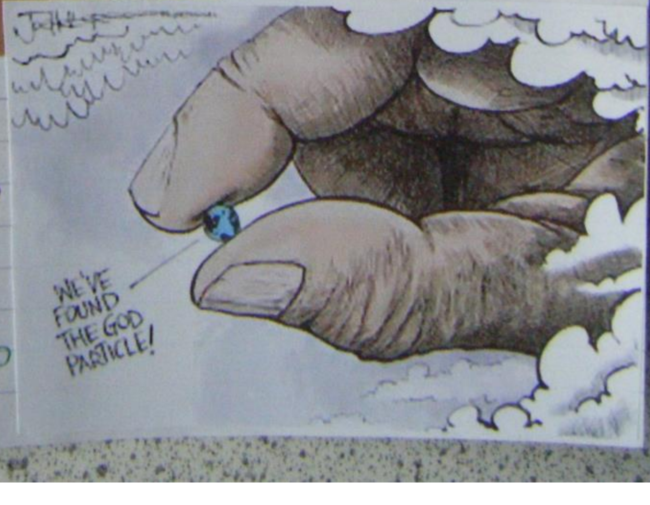
Many theories point to the existence of a further boson called the Higgs Boson, which has been referred to in some quarters as the 'God particle'.

This was predicted by Professor Peter Higgs at Edinburgh University 45 years before. This Higgs Boson particle has been confirmed by Scientists at CERN in Switzerland to have a mass around 133 times that of a proton.

ie $1.673 \times 10^{-27}\,\text{kg} \times 133 = \underline{\underline{2.225 \times 10^{-25}\,\text{kg}}}$

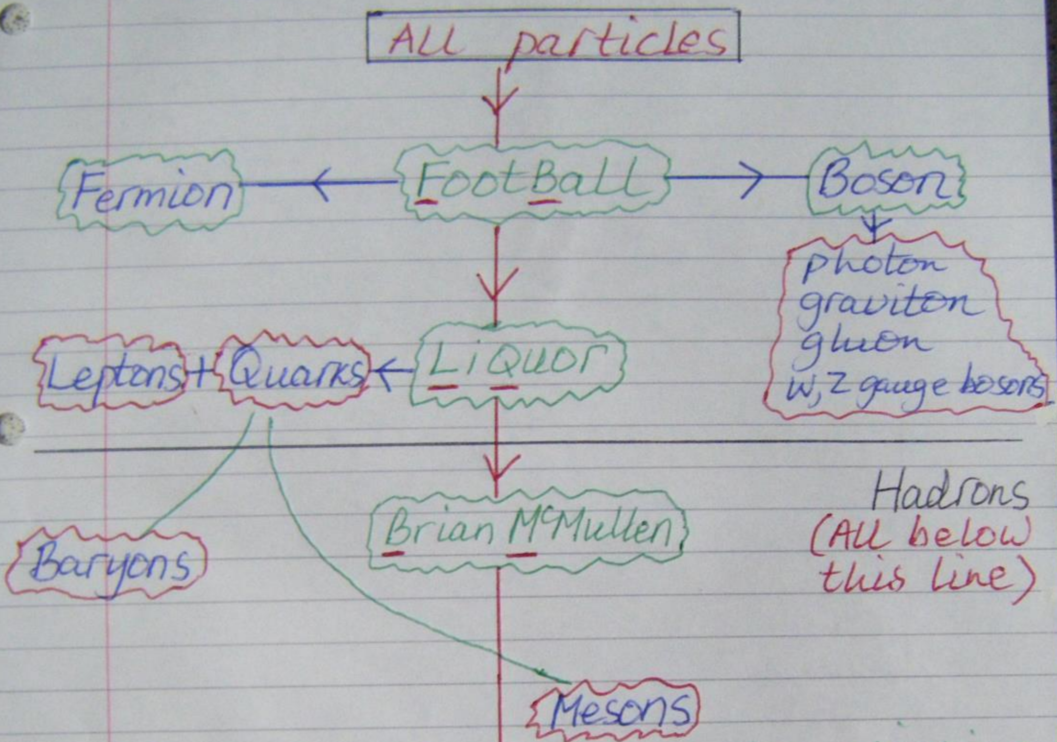


Higgs had proposed that the break in symmetry between the weak force and electromagnetic forces is a result of the Higgs field and its associated Higgs Boson.



- Where was Peter Higgs born and in which year?
- Where did he study as an undergraduate?

Particles Overview



* Bosons and fermions are like adjectives. They describe what they are like!! *

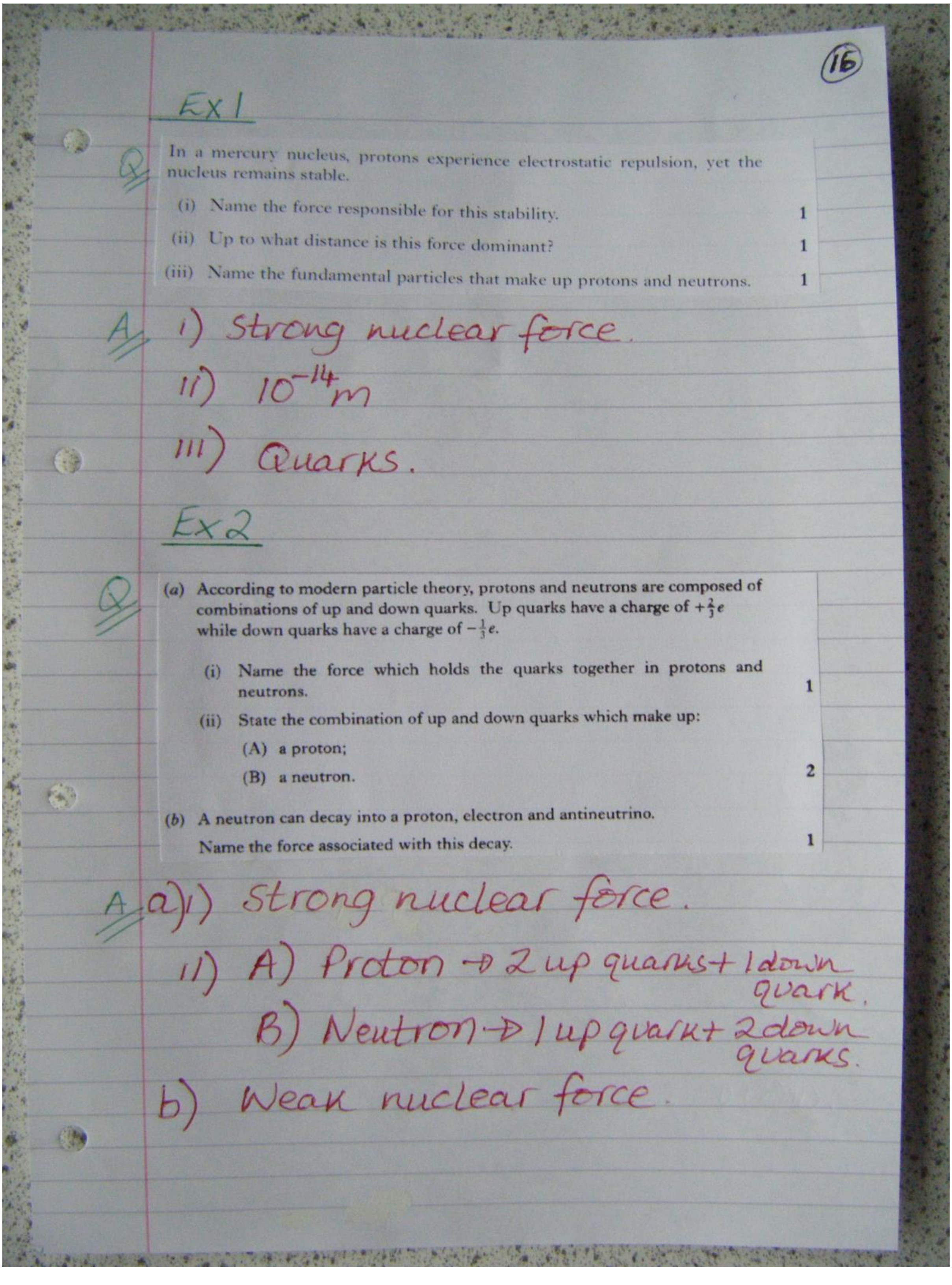
Farmyard Femions

T • The bull (tau) is heavy and slow. All he knows is from top to bottom.

M • The cow (muon) is charming but a little strange.

E • The calf (electron) cavorts up and down the field.

* If the tau, muon and electron are cattle then imagine neutrinos as fleas. (Relative Scale).



Ex 1

Q In a mercury nucleus, protons experience electrostatic repulsion, yet the nucleus remains stable.

(i) Name the force responsible for this stability. 1

(ii) Up to what distance is this force dominant? 1

(iii) Name the fundamental particles that make up protons and neutrons. 1

A i) Strong nuclear force.

ii) 10^{-14} m

iii) Quarks.

Ex 2

Q (a) According to modern particle theory, protons and neutrons are composed of combinations of up and down quarks. Up quarks have a charge of $+\frac{2}{3}e$ while down quarks have a charge of $-\frac{1}{3}e$.

(i) Name the force which holds the quarks together in protons and neutrons. 1

(ii) State the combination of up and down quarks which make up:

(A) a proton;

(B) a neutron. 2

(b) A neutron can decay into a proton, electron and antineutrino.

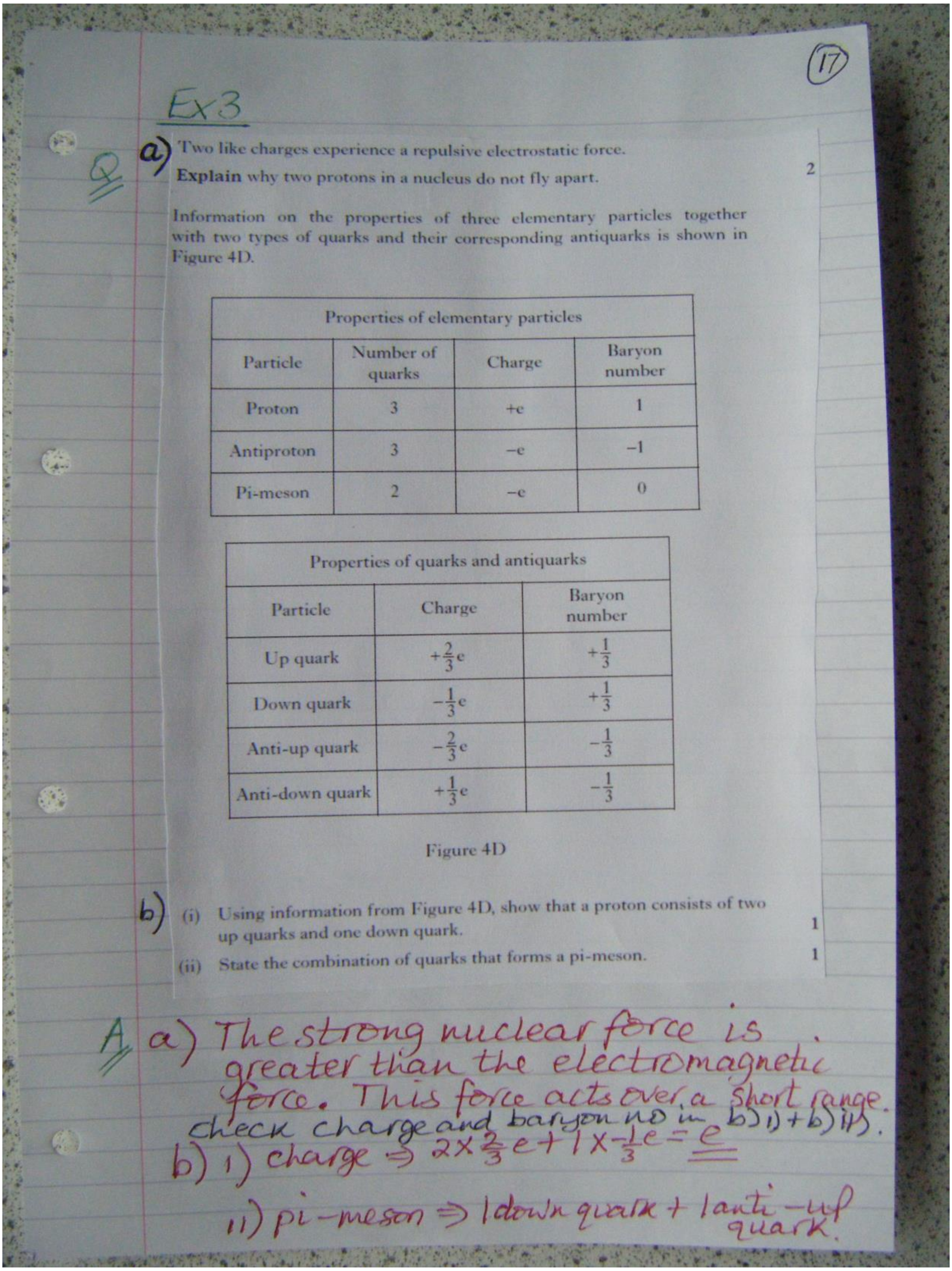
Name the force associated with this decay. 1

A a) i) Strong nuclear force.

ii) A) Proton → 2 up quarks + 1 down quark.

B) Neutron → 1 up quark + 2 down quarks.

b) Weak nuclear force.



Ex3

Q a) Two like charges experience a repulsive electrostatic force.

Explain why two protons in a nucleus do not fly apart. 2

Information on the properties of three elementary particles together with two types of quarks and their corresponding antiquarks is shown in Figure 4D.

Properties of elementary particles			
Particle	Number of quarks	Charge	Baryon number
Proton	3	+e	1
Antiproton	3	−e	−1
Pi-meson	2	−e	0

Properties of quarks and antiquarks		
Particle	Charge	Baryon number
Up quark	$+\frac{2}{3}e$	$+\frac{1}{3}$
Down quark	$-\frac{1}{3}e$	$+\frac{1}{3}$
Anti-up quark	$-\frac{2}{3}e$	$-\frac{1}{3}$
Anti-down quark	$+\frac{1}{3}e$	$-\frac{1}{3}$

Figure 4D

b) (i) Using information from Figure 4D, show that a proton consists of two up quarks and one down quark. 1

(ii) State the combination of quarks that forms a pi-meson. 1

A a) The strong nuclear force is greater than the electromagnetic force. This force acts over a short range.

check charge and baryon no in b) i) + b) ii).

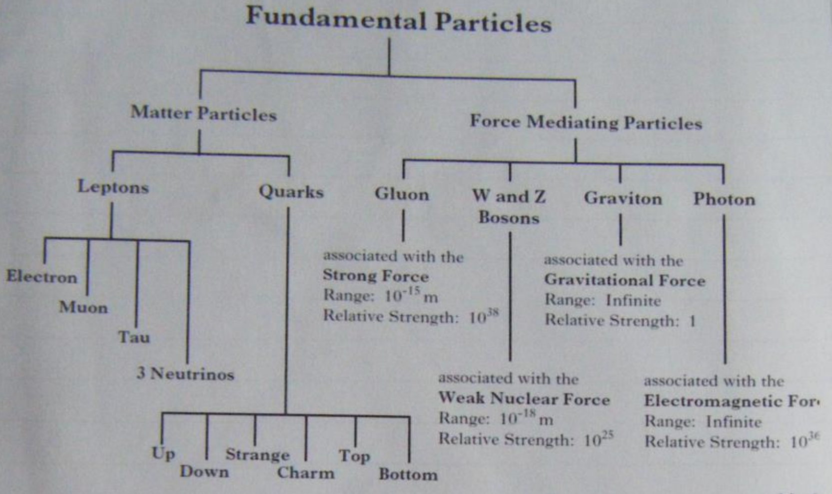
b) i) charge $\Rightarrow 2 \times \frac{2}{3}e + 1 \times -\frac{1}{3}e = \underline{\underline{e}}$

ii) pi-meson ⇒ 1 down quark + 1 anti-up quark.

Ex4

Q

26. The following diagram gives information on the Standard Model of Fundamental Particles and Interactions.



Mark

Use information from the diagram and your knowledge of physics to answer the following questions.

(*a*) Explain why particles such as leptons and quarks are known as *Fundamental Particles*. **1**

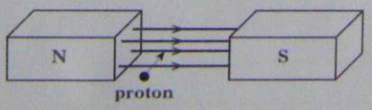
(*b*) A particle called the sigma plus (Σ^+) has a charge of +1. It contains two different types of quark. It has two up quarks each having a charge of $+^2/_3$ and one strange quark.

What is the charge on the strange quark? **1**

(*c*) Explain why the gluon cannot be the force mediating particle for the gravitational force. **1**

(*d*) In the Large Hadron Collider (LHC) beams of hadrons travel in opposite directions inside a circular accelerator and then collide. The accelerating particles are guided around the collider using strong magnetic fields.

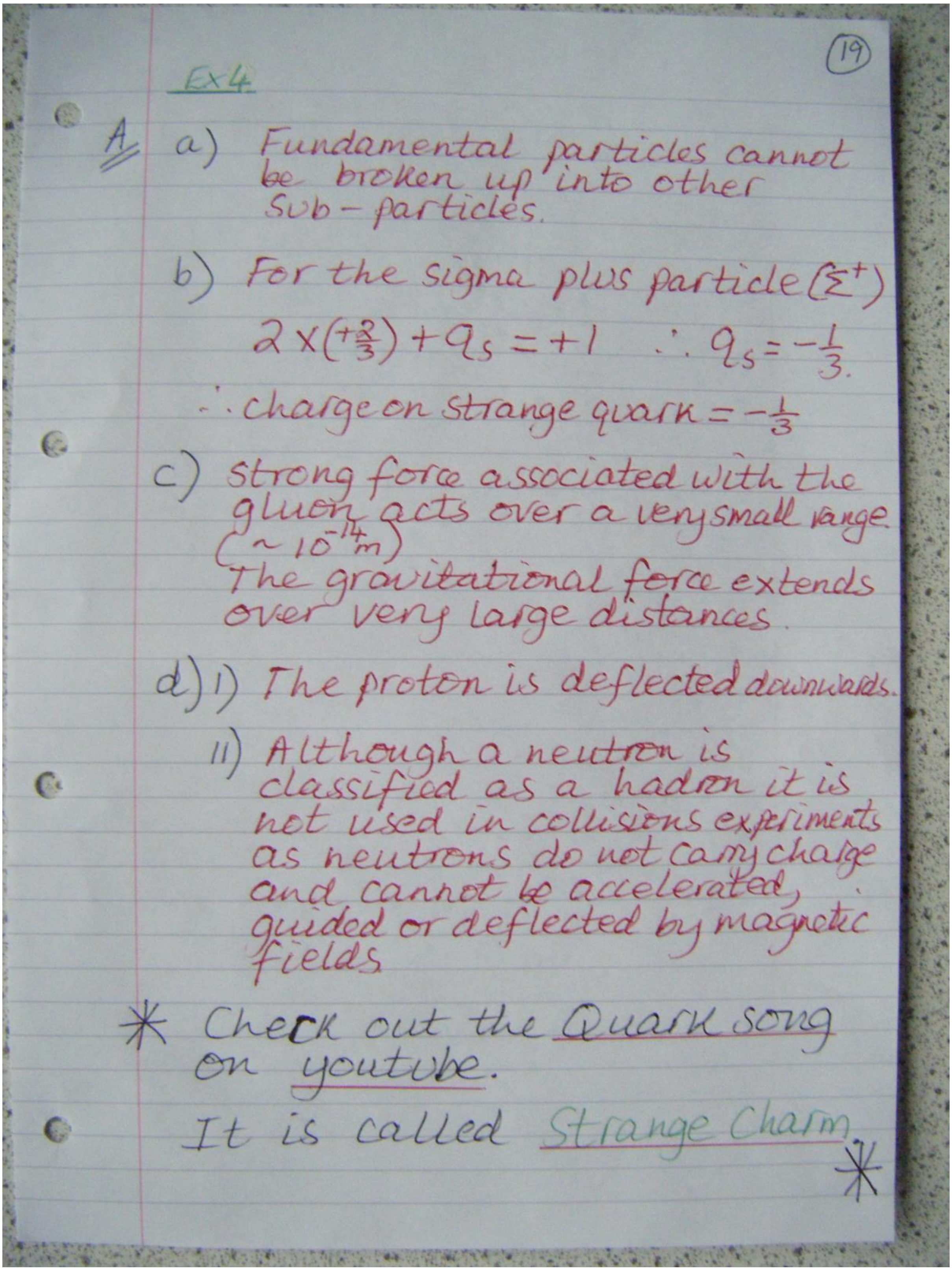
(i) The diagram shows a proton entering a magnetic field.



In which direction is this proton deflected? **1**

(ii) The neutron is classified as a hadron.

Explain why neutrons are **not** used for collision experiments in the LHC. **1**



Ex 4.

A a) Fundamental particles cannot be broken up into other sub-particles.

b) For the sigma plus particle (Σ^+)

$2 \times (+\frac{2}{3}) + q_s = +1 \quad \therefore q_s = -\frac{1}{3}.$

$\therefore$ charge on strange quark $= -\frac{1}{3}$

c) strong force associated with the gluon acts over a very small range. ($\sim 10^{-14}$ m)
The gravitational force extends over very large distances.

d) I) The proton is deflected downwards.

II) Although a neutron is classified as a hadron it is not used in collisions experiments as neutrons do not carry charge and cannot be accelerated, guided or deflected by magnetic fields

* Check out the Quark song on youtube.

It is called Strange Charm *