THE ATOM

Ernest Rutherford 1902

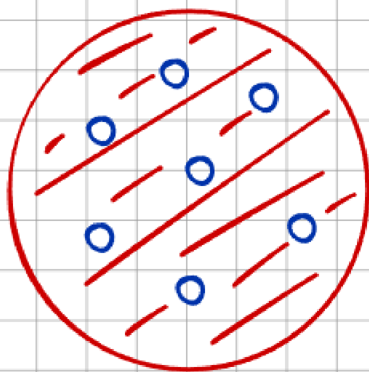
Separated the emissions from various radioactive sources into three categories; ALPHA, BETA, GAMMA
He began to experiment with them, in particular ALPHA radiation.

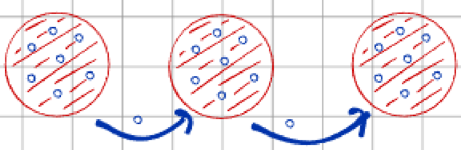
JJ Thomson 1904

Thomson theorised that Dalton's billiard ball is incomplete, and that in fact the atom is a JIGSAW PUZZLE of positive and negative charge, leading to overall neutrality.

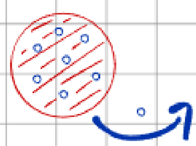
The Plum Pudding Model

consists of positive atom with electrons RANDOMLY DISTRIBUTED within the structure.



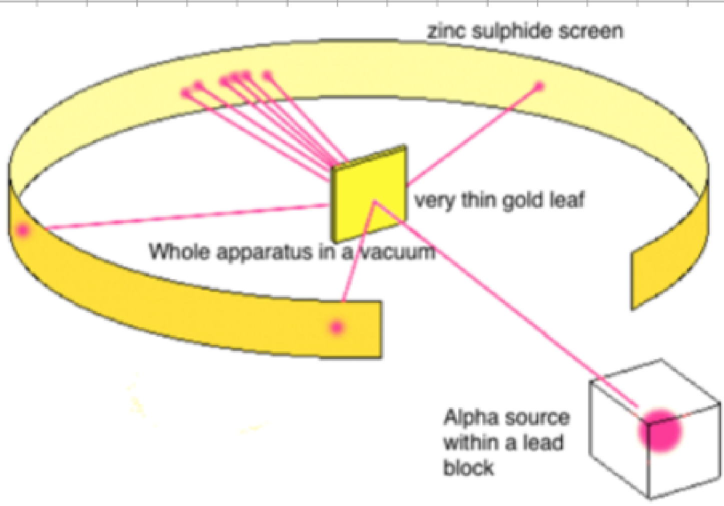


conduction



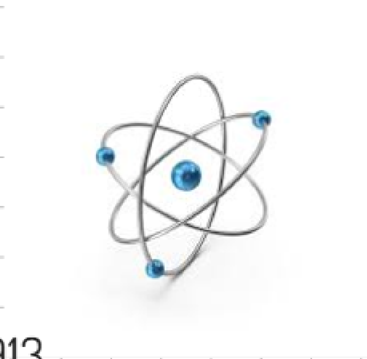
ionisation

Ernest Rutherford 1911



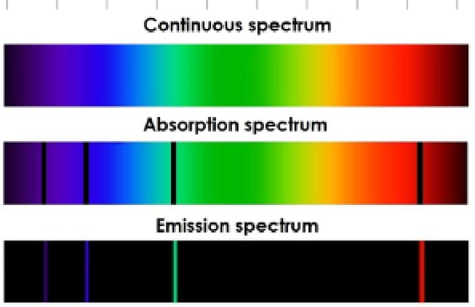
An experiment performed under vacuum to attempt to confirm the plum pudding model.

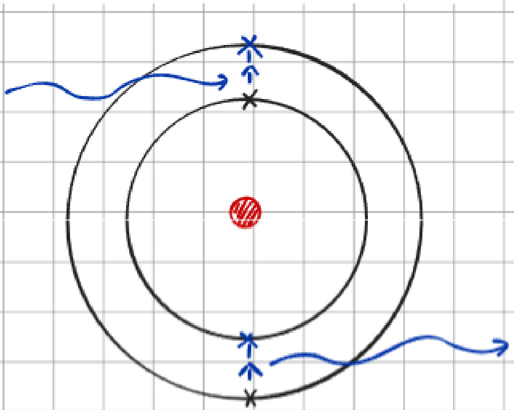
OBSERVATION	CONCLUSION
Most alpha particles are undeflected	The atom is mostly empty space
There are some small angle deflections.	The nucleus is a charged region
Very few particles are backscattered.	The nucleus is SMALL, POSITIVE and MASSIVE



The Planetary Model of the Atom

Niels Bohr 1913





Bohr observed the interactions of various elements with white light, and noticed that DISCRETE FREQUENCIES were missing.

This led Bohr to the idea of DISCRETE ENERGY LEVELS within atoms, and that ELECTRONS were able to MOVE BETWEEN levels if energy were provided from outside the atom.

FURTHER DEVELOPMENTS BEYOND THE ATOM

Ernest Rutherford 1917

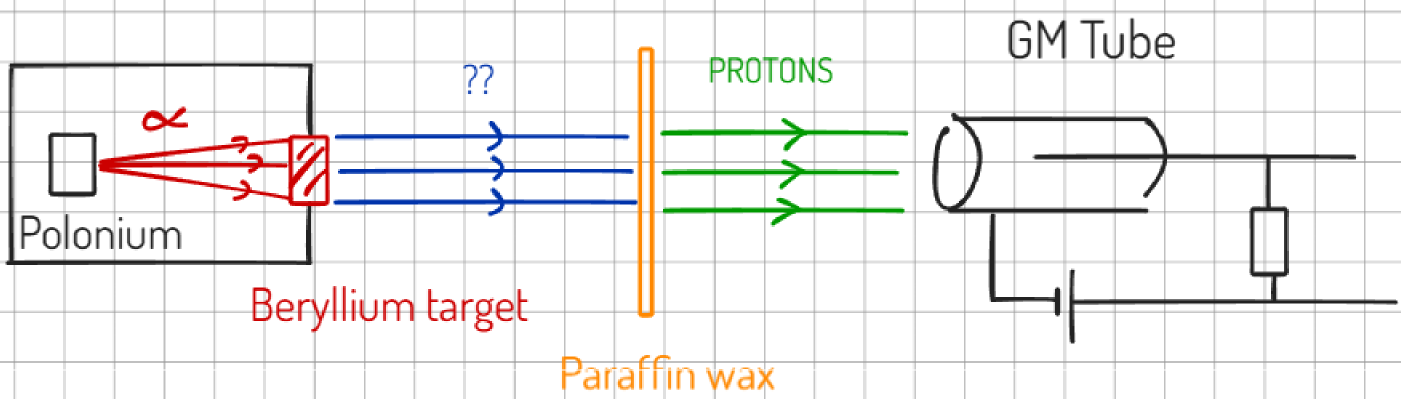
Rutherford was able to detect Hydrogen nuclei when alpha particles were directed at air.

He found that the same nuclei were detected when he used a range of ELEMENTAL GASES.

This lead him to conclude that the Hydrogen nucleus was a component of all other nuclei. (The PROTON)

The nucleus is made of protons, and has electrons orbiting it in discrete energy levels.

James Chadwick 1932

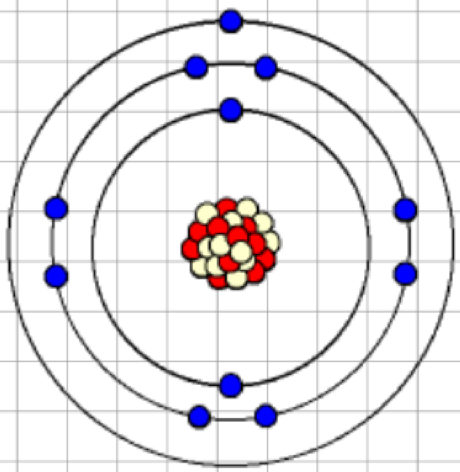


Chadwick noticed that lightweight metals emitted particles, which were heavy enough to knock protons out of paraffin.
They were unresponsive to an Electromagnetic field, and difficult to detect.

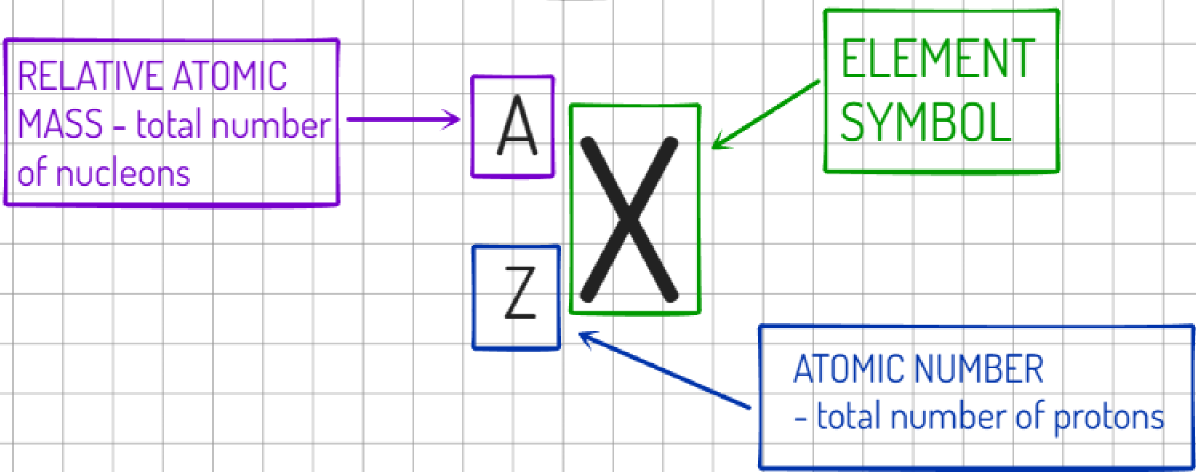
The eventual conclusion was that they were another type of NUCLEON (particle from the nucleus), which held NO CHARGE.
They were named NEUTRONS.

THE GCSE ATOM

particle	Q (C)	relative Q	m (kg)	relative m
proton	$+1.6\times10^{-19}$	+1	1.67×10^{-27}	1
neutron	0	0	1.67×10^{-27}	1
electron	-1.6×10^{-19}	−1	9.11×10^{-31}	0.0005



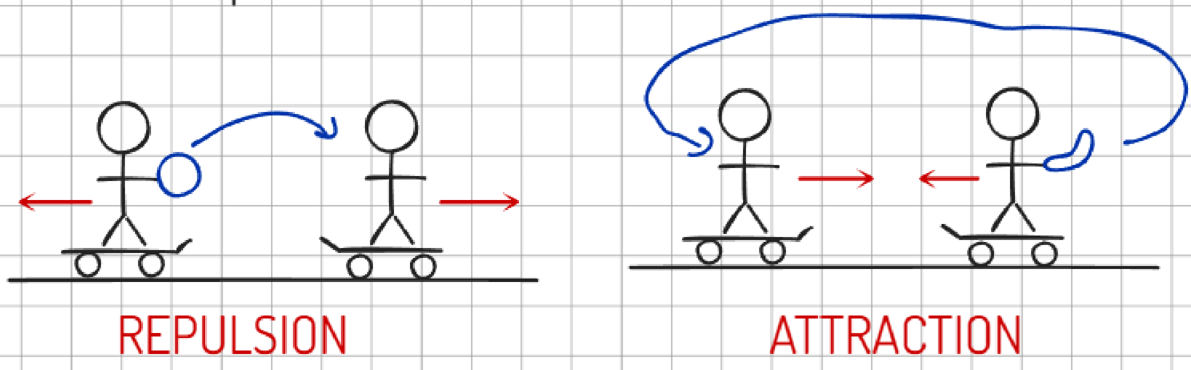
An isotope is an atom with the same number of protons but a different number of neutrons.



FUNDAMENTAL INTERACTIONS

There are four fundamental forces that allow particles to interact with one another.
On a macroscopic scale, charges and masses interact using CLASSICAL FIELD THEORY.
On a QUANTUM SCALE, these interactions are mechanically very different to the 'forces' we consider in a Newtonian setting.

This breakdown at a QUANTUM level means we need to reconsider how particles interact.



Particles interact via EXCHANGE PARTICLES (Force Mediators)

The ELECTROMAGNETIC Interaction (Quantum Electrodynamics)

Affects: Charged particles.

Effective range: Infinite — but the magnitude of the force decreases according to the INVERSE SQUARE LAW

$F \propto \frac{1}{r^2}$

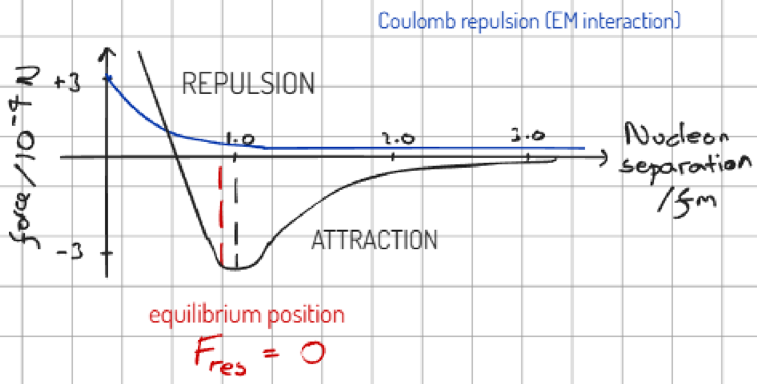
Relative strength: 1/137

Mediator: Virtual photon γ (transfer of energy but no mass)

The STRONG Nuclear Force (Quantum Chromodynamics)

Affects: only quarks

Effective range:



Relative strength: 1

Mediator(s): within the nucleus, between quarks - Gluons g
over longer ranges - Pions π

The WEAK Nuclear Force (Quantum Flavourdynamics)

Affects: all fermions (all baryons and leptons)

Effective range: 10^{-18} m

all DECAY interactions occur by the weak interaction

$$n \longrightarrow p + e^-$$

(GCSE version)

Relative Strength: $1/10^6$

Mediators: W^-, W^+, Z^0 bosons

Gravity (Quantum Gravitation)

Affects: particles with mass

Effective range: infinite

Relative strength: 6×10^{-39}

Mediator: graviton?

NUCLEAR INSTABILITY

21/09/23

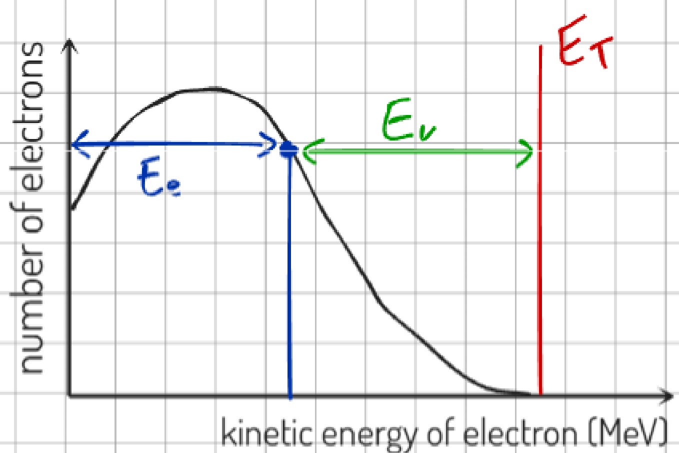
Interaction	Nature	Mediator(s)
Gravity	mass	graviton?
Electromagnetic	charge	virtual photon
Strong Nuclear	quarks	gluon (or pion)
Weak Nuclear	fermion decay	W^+, W^-, Z^0

Not all nuclei are energetically stable. Nuclei can increase their stability by losing energy by NUCLEAR DECAY.
There are 3 DOMINANT MECHANISMS for this. These are:

α β^- γ

Alpha decay involves the emission of a HELIUM NUCLEUS (composed of 2 protons and 2 neutrons).

Beta minus decay involves a neutron decays into a proton and emits an electron and an anti-electron neutrino



The energy lost by the nucleus in a beta minus decay event is always equal to E_T

The energy of a random electron selected is E_e

The energy deficit is E_ν

Another particle was emitted along with the electron.
- no mass or charge
- needs to be an anti-lepton

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

Gamma decay involves the nucleons emitting an electromagnetic wave and relaxing to a lower nuclear energy level.

NUCLEAR EQUATIONS

α	β^-	γ
$^{39}_{94}Pu \rightarrow ^{235}_{92}U + ^{4}_{2}\alpha$	$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}_e$	$^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + ^{0}_{0}\gamma$

DETECTING IONISING RADIATION

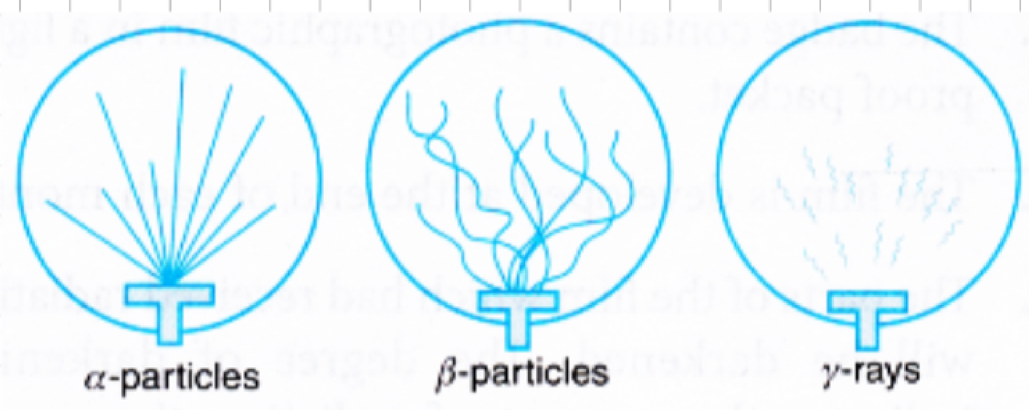
Photographic film

Particles incident on photographic film can interact in a similar way to EM radiation and cause discolouration.
(Recall GCSE X-rays)

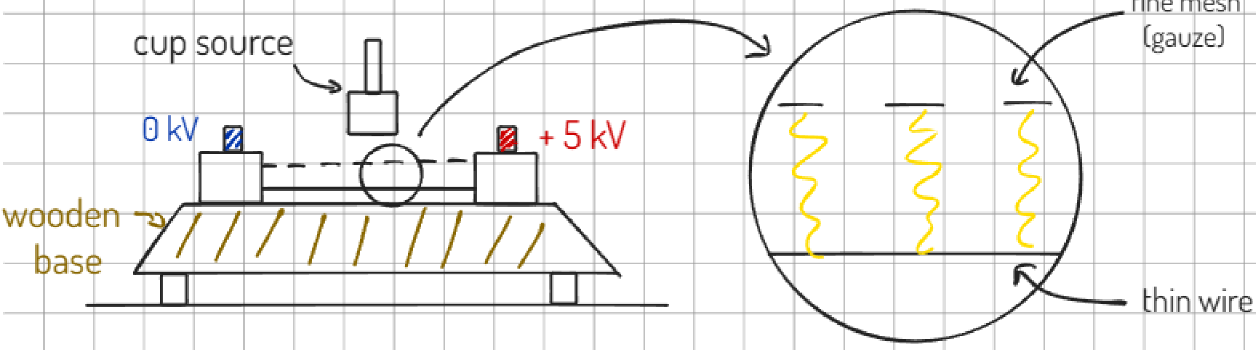
Cloud chamber

If ionising radiation passes through a sealed chamber of air which has been SATURATED with water vapour, then the passage of the ionising radiation will form a CLOUD TRAIL.

A magnetic field can show us the polarity and specific charge of the incident particles.



Spark Counter

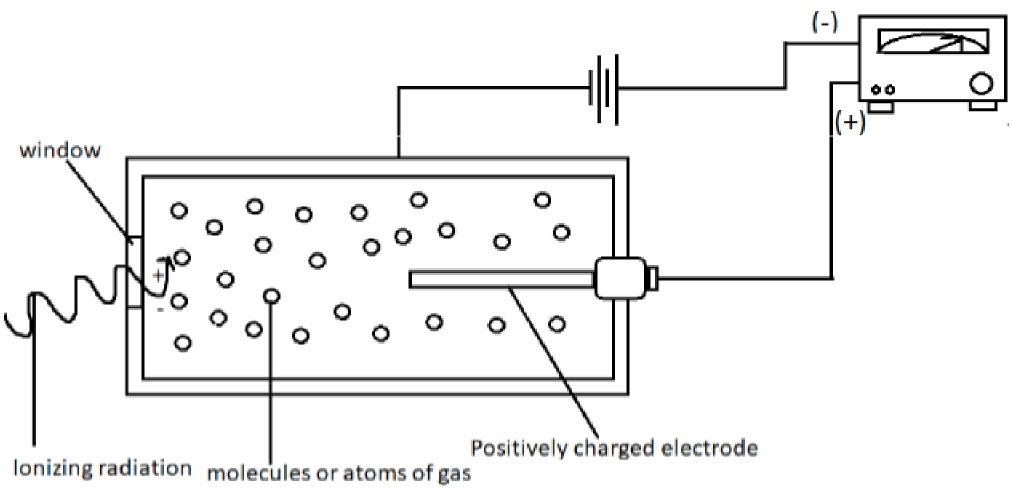


Ionised air molecules allow a spark to travel between the gauze and the thin wire. The sparks can then be counted.

(Only useful for alpha emissions)

GM Tube

Ionised components of the gas reach the electrode, sending a pulse of current, recording a count.



ANTIPARTICLES AND PHOTONS

The particle model of electromagnetic radiation suggests that there is a fundamental QUANTUM unit of energy, and that radiation is emitted and absorbed in DISCRETE amounts.

A discrete packet of EM radiation is called a PHOTON.

$$E = hf$$

(J) (Js) (Hz)

energy of photon = Planck's constant x frequency of EM radiation

$h = 663 \times 10^{-34}$ Js

Nuclear Energies

The energy of sub-nuclear particles is not usually expressed in Joules, as the values would be very small. They are instead expressed in Mega-electron volts.

One electron volt is 1.6×10^{-19} J
(the charge on one electron in Joules)

$$1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$$

Antiparticles

In 1928, Paul Dirac mathematically supposed the existence of the POSITRON.
He suggested that this particle has the same REST MASS ENERGY, as an electron, but had a POSITIVE CHARGE.

the energy released if ALL the mass was converted to energy when the particles was AT REST.

$E = mc^2$

Strangely, antiparticles are not common
the Universe appears overwhelmingly made of matter.

Antimatter only becomes apparent in high energy interactions.

All antiparticles that have been discovered have, as Dirac predicted, identical rest mass energies, but opposite charges to their matter counterparts.
The general notation is to place a bar over the symbol for the matter particle (with the exception of the positron).

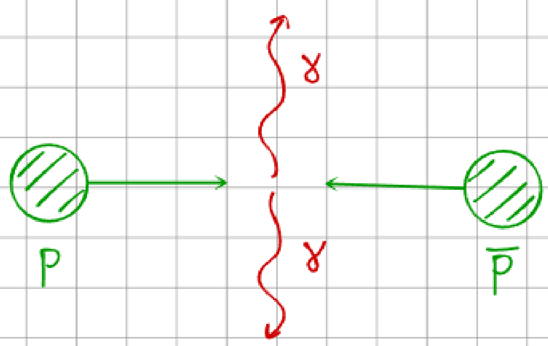
PARTICLE	SYMBOL	Q_R	Mass (kg)	E_0 (MeV)
proton anti-proton	p $\bar{p}$	+1 -1	$1.67(3) \times 10^{-27}$	938.3
neutron anti-neutron	n $\bar{n}$	0 0	$1.67(5) \times 10^{-27}$	939.6
electron positron	e^- e^+	-1 +1	9.11×10^{-31}	0.511
electron neutrino anti-electron neutrino	ν_e $\bar{\nu}_e$	0 0	0	0

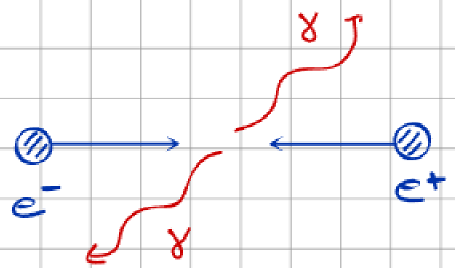
Matter - Antimatter Interactions

Key conservation laws (GCSE)
1. Conservation of energy
2. Conservation of momentum
3. Conservation of charge

When a particle and antiparticle meet they ANNIHILATE one another.
The total mass of BOTH particles is converted into energy.
In order to conserve momentum, TWO PHOTONS are released.

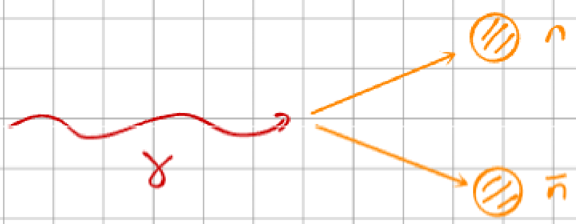
(in opposite directions)





The total energy of the two photons is equal to the total rest mass energy of the particle - antiparticle pair.

A PHOTON with enough energy can interact with a large nucleus and be converted into a PARTICLE - ANTIPARTICLE pair. This is called PAIR PRODUCTION.



1. Calculate the total energy of each photon released when an electron and positron meet assuming that they are at rest.

0.51 MeV each

Total = 1.02 MeV

photon energy = 0.51 MeV ✓1 as 2 γ are released

2. What is the wavelength of a photon that has sufficient energy to produce a neutron and antineutron pair?

(Hint $c = f\lambda$) $f = \frac{c}{\lambda}$

$E = \frac{hc}{\lambda}$ ✓1 $\lambda = \frac{hc}{E}$

$\lambda = \frac{6.6\times10^{-34} \times 3\times10^{8}}{(939.6\times2) \times 1.6\times10^{-13}}$ ✓2

$= 6.62\times10^{-16}$ m ✓3

3. A proton with a kinetic energy of 15 MeV meets a stationary antiproton. What is the frequency of the photons produced?

$E_{total} = (938.3\times2)$ ✓1 $+ 15$ ✓2 $= 1891.6$ MeV

$E_{photon} = 945.8$ MeV ✓3

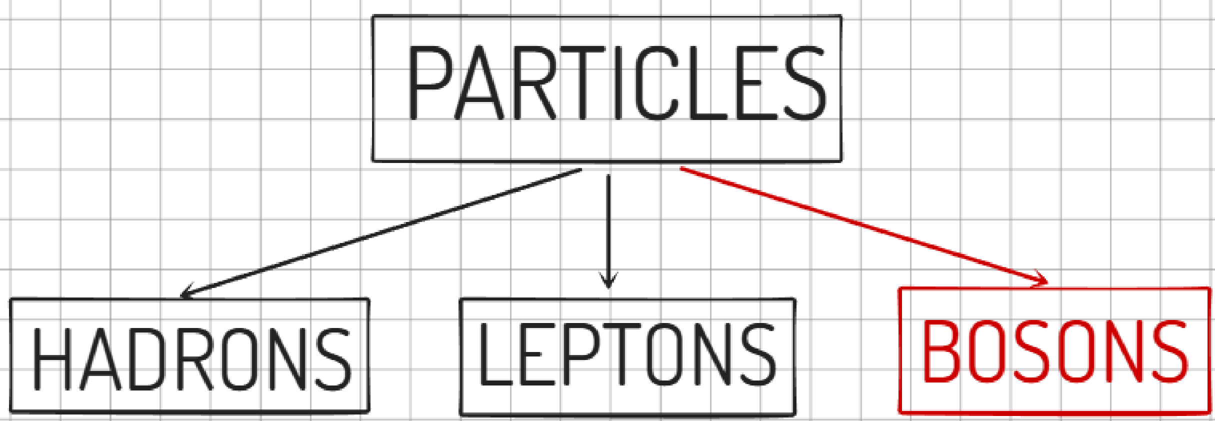
$f = \frac{E}{h} = 2.28\times10^{23}$ Hz ✓4

don't forget to convert to J (LIKE I DID)

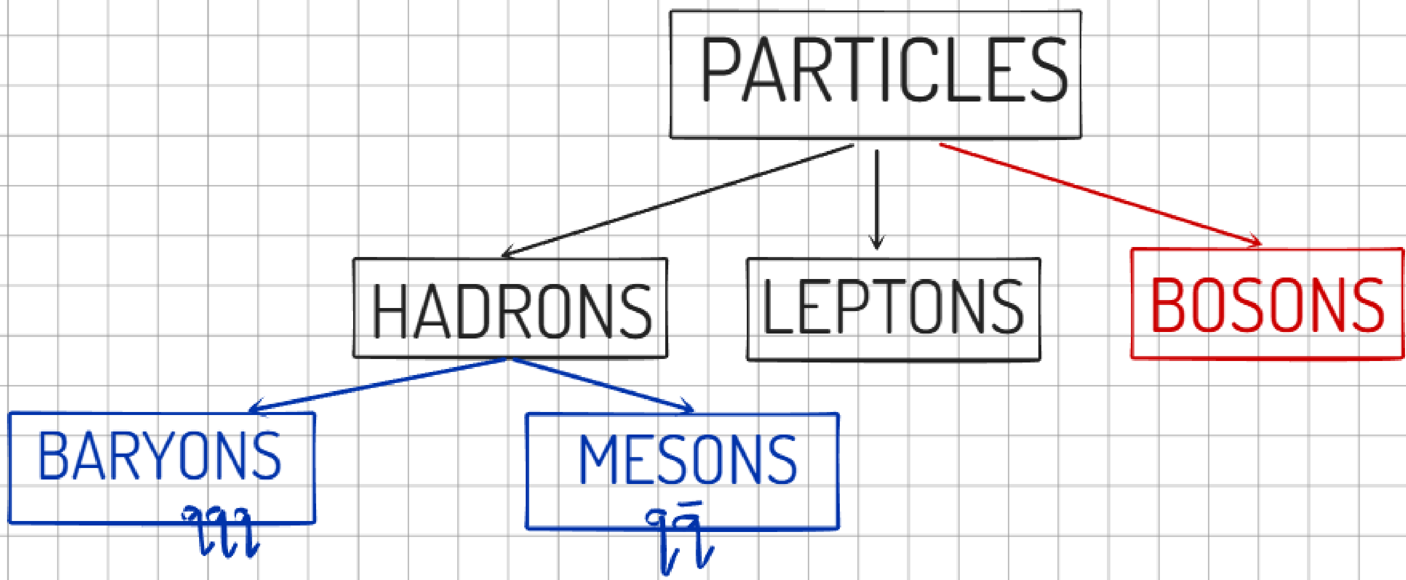
6.6×10^{-34}

$945.8 \times 1.6\times10^{-13}$

THE PARTICLE ZOO



All particles can be classified according to their properties. We categorise them by which interactions they are capable of.



Any particle which is capable of experiencing the STRONG INTERACTION is classified as a HADRON. ALL HADRONS are composed of QUARKS.

BARYONS

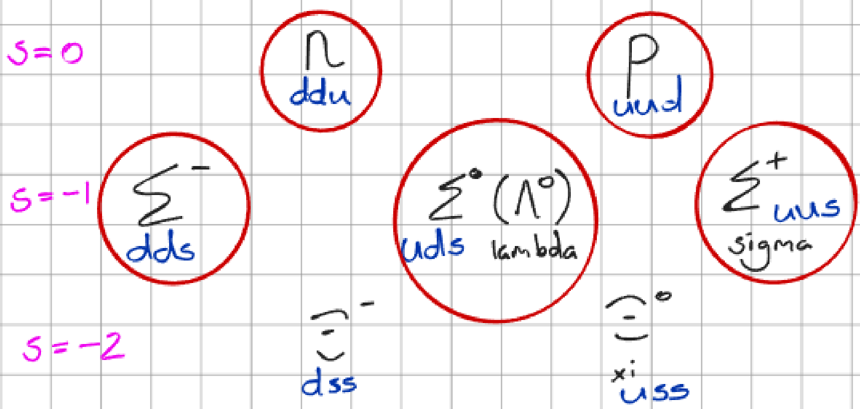
Are hadrons which are composed of three quarks. All baryons except the FREE PROTON are UNSTABLE. They will decay by the WEAK INTERACTION.

Every particle has a BARYON NUMBER.

B = +1 if it is a baryon.
B = 0 if it is NOT a baryon.
B = -1 if it is an anti-baryon ($\bar{q}\bar{q}\bar{q}$)

The Eightfold Way

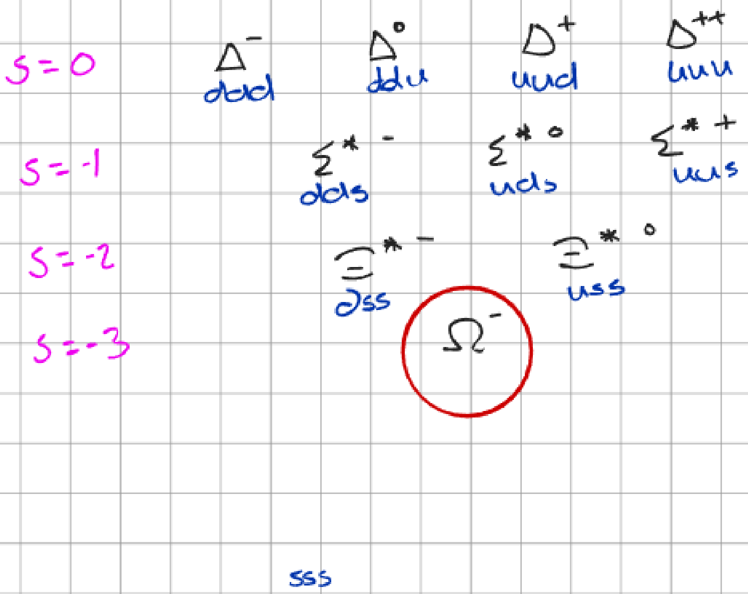
(Spin 1/2 Octet)
[Low Energy]



STRANGENESS is a fundamental quantity of the STRANGE QUARK

S = -1 if strange
S = +1 if anti-strange

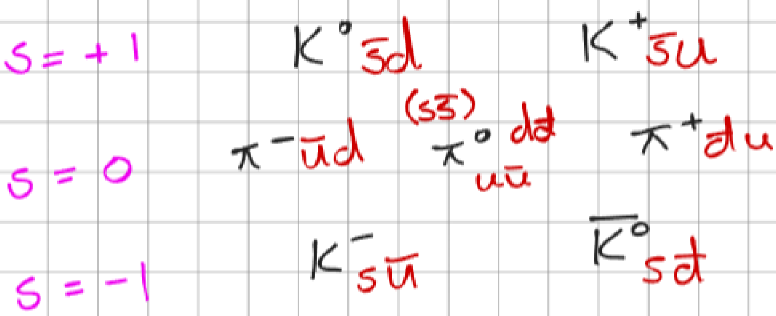
(Spin 3/2 Octet)
[*High Energy]



MESONS

Mesons are hadrons composed of a quark, anti-quark pair. $(q\bar{q})$
They experience the STRONG INTERACTION and have a BARYON NUMBER of 0. All mesons are UNSTABLE

(Spin 0 Octet)



Quark	m	Q
u	+1/3	+2/
d	+1/3	-1/3
s	+1/3	-1/3

LEPTONS

Leptons are FUNDAMENTAL PARTICLES which do NOT experience the STRONG INTERACTION. ELECTRONS are the only STABLE lepton.

Each lepton has its own LEPTON NUMBER. All hadrons have a LEPTON NUMBER of 0.

NAME	SYMBOL	Q_R	L_e	L_μ	L_τ
electron	e^-	-1	+1	0	0
positron	e^+	+1	-1	0	0
electron neutrino	ν_e	0	+1	0	0
anti-electron neutrino	$\bar{\nu}_e$	0	-1	0	0
muon	μ	-1	0	+1	0
anti-muon	$\bar{\mu}$	+1	0	-1	0
muon neutrino	ν_μ	0	0	+1	0
anti-muon neutrino	$\bar{\nu}_\mu$	0	0	-1	0
tau	τ	-1	0	0	+1
anti-tau	$\bar{\tau}$	+1	0	0	-1
tau neutrino	ν_τ	0	0	0	+1
anti-tau neutrino	$\bar{\nu}_\tau$	0	0	0	-1

NOTE: Spin 1/2 Baryons and Leptons are both FERMIONS

CONSERVATION LAWS

We can determine if a particle interaction is viable if various conservation laws are observed to be met.

CHARGE

The total charge BEFORE and AFTER an interaction must be the SAME.

BARYON NUMBER

There must be the SAME NUMBER of baryons (or anti-baryons) present before and after an interaction.

LEPTON NUMBER

Each lepton number (L_e, L_μ, L_τ) must be conserved independently. (consider the particles involved)

STRANGENESS

Strangeness is SOMETIMES CONSERVED.
It is conserved in STRONG INTERACTIONS, but is NOT conserved in WEAK INTERACTIONS.

$$K^+ \longrightarrow \mu^+ + \nu_\mu$$

K^+: $\bar{s}u$; μ^+ (or $\bar{\mu}$)

	K^+		μ^+		ν_μ	
Q	+1	=	+1	+	0	✓
B	0	=	0	+	0	✓
S	+1	=	0	+	0	✓ weak
L_e	0	=	0	+	0	✓
L_μ	0	=	-1	+	+1	✓
L_τ	0	=	0	+	0	✓

This interaction IS POSSIBLE. It is a WEAK interaction, so would be called KAON DECAY

$$\Lambda^0 \longrightarrow \pi^- + e^+ + \nu_e$$

Q	0	=	−1	+	+1	+	0	✓
B	+1	=	0	+	0	+	0	✗

This interaction is IMPOSSIBLE. Baryon number is NOT CONSERVED

$$\pi^- + p \longrightarrow x_1 + \overline{K}^0$$

$$p + p \longrightarrow x_2 + K^- + p$$

$$K^+ + n \longrightarrow x_3 + \pi^0 + \pi^0$$

1) What are the baryon numbers of x_1, x_2 & x_3 ?

2) What are the charges of x_1, x_2 & x_3 ?

3) What are the strangenesses of x_1, x_2 & x_3 ?

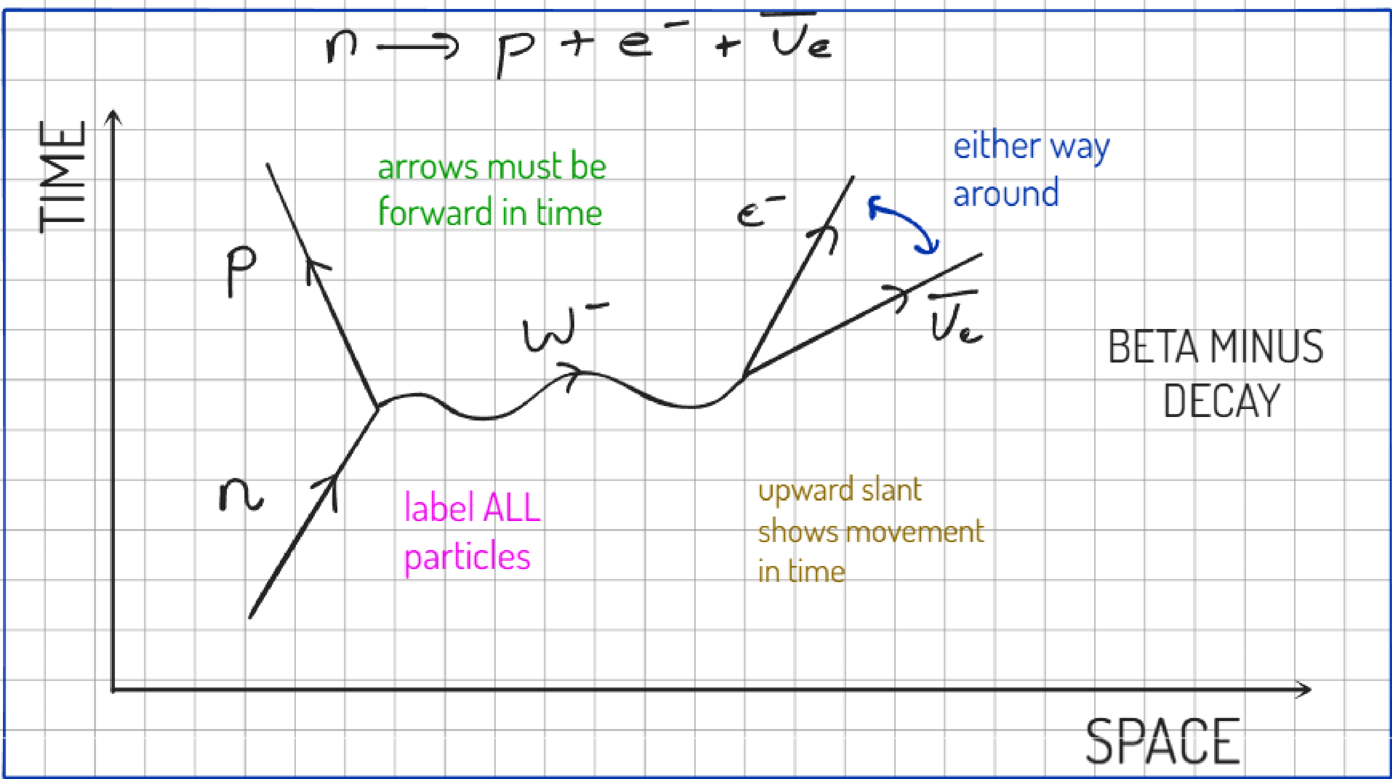
4) What particle is x_2 ?

4) All x particles decay via the weak interaction write a possible decay for x_2 .

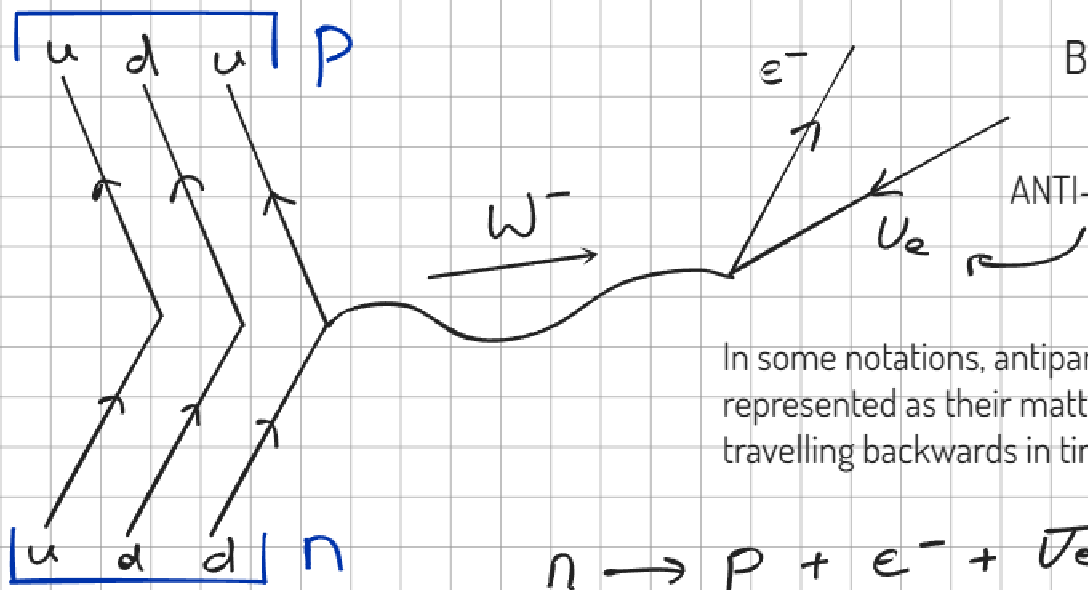
FEYNMAN DIAGRAMS

A clear way of representing any interaction.

The rules are:
- the y axis represents TIME
- the x axis represents SPACE
- gauge bosons (force mediators) are represented by a wavy line or helix
- all PARTICLES are represented by straight lines
- each line MUST have an ARROW
- all conservation laws must be applied
- particles lines can NEVER cross



BETA MINUS DECAY

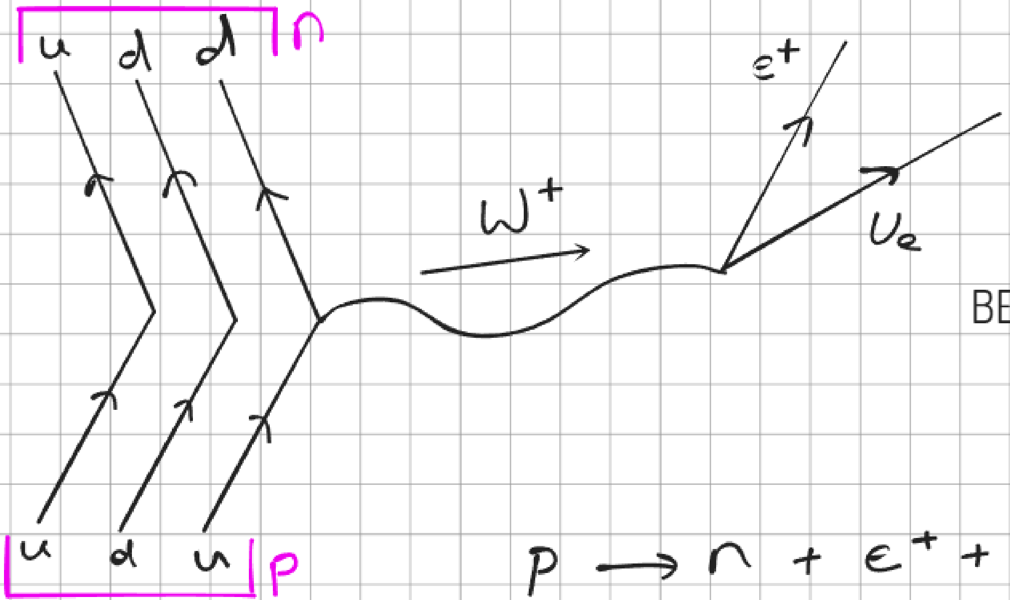


ANTI-electron neutrino

In some notations, antiparticle are represented as their matter counterpart travelling backwards in time

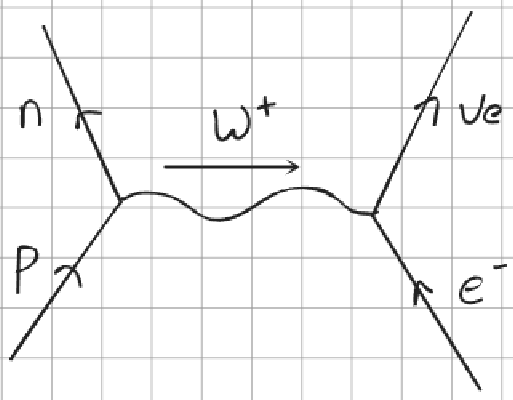
$$n \rightarrow p + e^- + \bar{\nu}_e$$

BETA PLUS DECAY



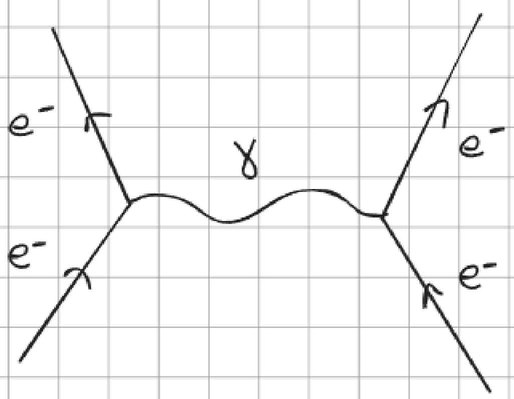
$$p \rightarrow n + e^+ + \nu_e$$

ELECTRON CAPTURE BY PROTON

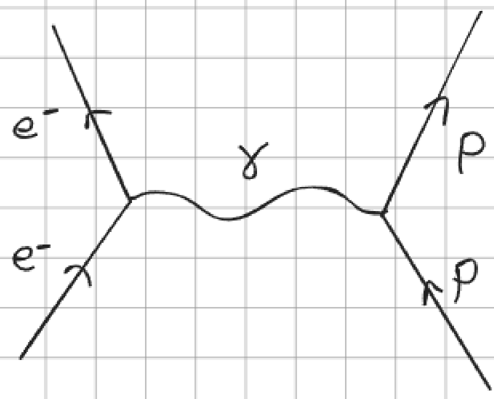


ELECTRON COLLISION WITH A PROTON

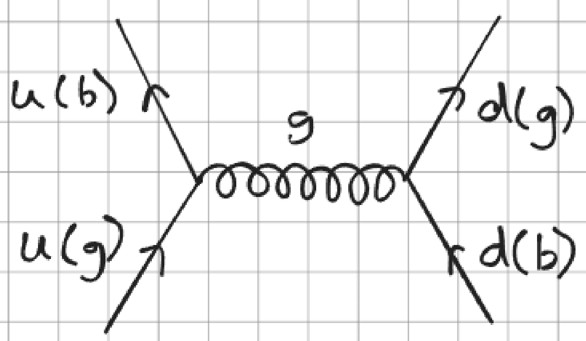
$$p + e^- \longrightarrow n + \nu_e$$



ELECTROSTATIC REPULSION



ELECTROSTATIC ATTRACTION



NUCLEON COLOUR BINDING

NOT NEEDED FOR SPECIFICATION