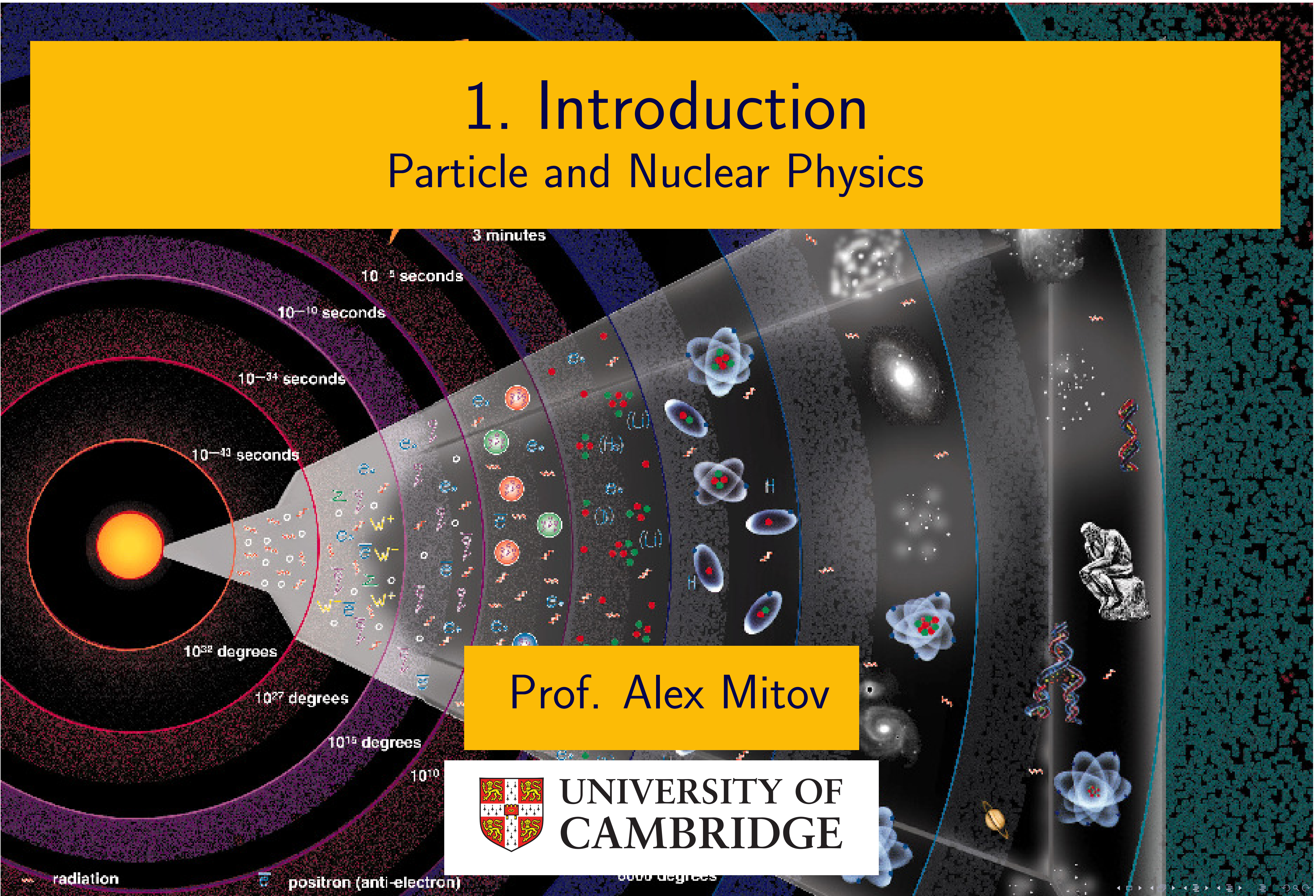
1. Introduction
Particle and Nuclear Physics



Prof. Alex Mitov

UNIVERSITY OF CAMBRIDGE

In this section...

- Course content
- Practical information
- Matter
- Forces

Course content

These lectures will cover the core topics of Particle and Nuclear physics.

Particle Physics is the study of

Matter: Elementary particles

Forces: Basic forces in nature
Electroweak (EM & weak)
Strong

Current understanding is embodied in the

Standard Model

which successfully describes all current data*.

Nuclear Physics is the study of

Matter: Complex nuclei
(protons & neutrons)

Forces: Strong "nuclear" force
(underlying strong force)
+ weak & EM decays

Complex many-body problem, requires semi-empirical approach.

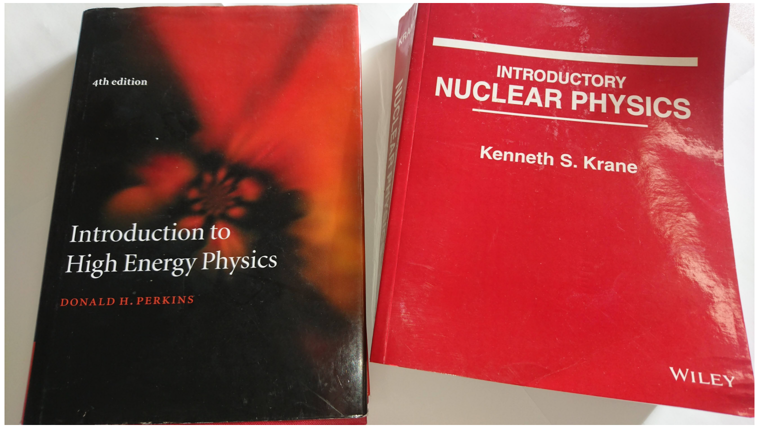
Many models of Nuclear Physics.

Historically, Nuclear Physics preceded and led to Particle Physics.
Our course will discuss Particle Physics first, and then Nuclear Physics.

* *with some interesting exceptions!*

Practical information

Website holds course information, notes, appendices and problem sheets
https://www.precision.hep.phy.cam.ac.uk/people/mitov/pnp/



Books

Introduction to High Energy Physics, Perkins
Introductory Nuclear Physics, Krane

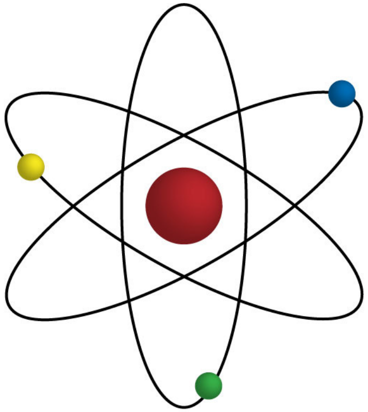
Lecturing material provided as **three handouts**.
Lectures will cover additional examples – please attend!!

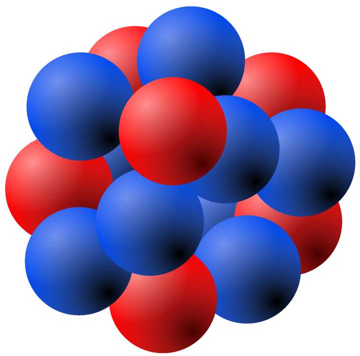
Problem sets in 4 parts

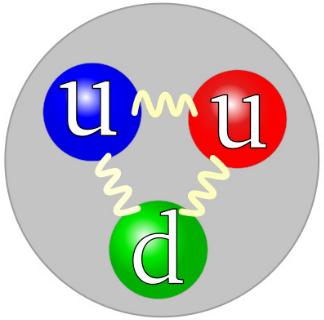
Part 1, q. 1-10: Chapters 1-4
Part 2, q.11-22: Chapters 5-8
Part 3, q.23-30: Chapters 9-12
Part 4, q.31-44: Chapters 13-16

My availability: after lectures, or contact via email (adm74@cam.ac.uk)

Zooming into matter







Atom *Binding energy* $\sim$ *Rydberg* ~ 10 eV

Electrons bound to atoms by EM force

- Size: Atom $\sim 10^{-10}$m, $e^- < 10^{-19}$m
- Charge: Atom is neutral, electron $-e$
- Mass: Atom mass $\sim$ nucleus, $m_e = 0.511 MeV/c^2$
- Chemical properties depend of Atomic Number, Z

Nucleus *Binding energy* ~ 10 MeV/*nucleon*

Nuclei held together by strong "nuclear" force

- Size: Nucleus (medium Z) ~ 5 fm (1 fm$= 10^{-15}$ m)

Nucleon *Binding energy* ~ 1 GeV

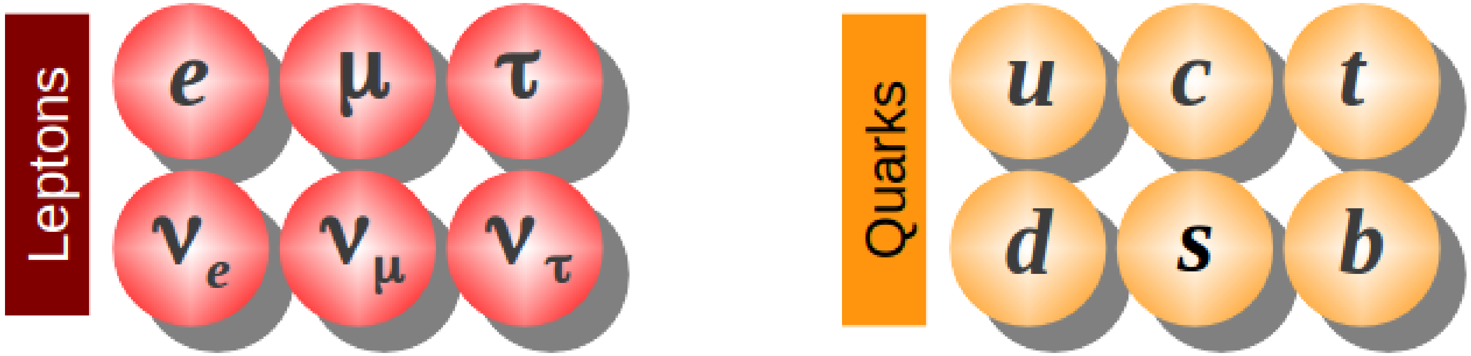
Protons & neutrons held together by the strong force

- Size: p, n ~ 1 fm
- Charge: proton $+e$, neutron is neutral
- Mass: p, n $= 939.57$ MeV$/c^2 \sim 1836\, m_e$

Matter

In the Standard Model, all matter is made of spin $\frac{1}{2}$ fundamental particles.

There are two types, each with 3 generations:



Consequence of relativity and quantum mechanics (Dirac equation)

Antiparticle for every existing particle: identical mass, spin, energy, momentum, **but** has the opposite sign of interaction (e.g. electric charge).

Particles and antiparticles

- electron e^- & positron e^+
- up quark u ($Q = +\frac{2}{3}$) & antiup $\bar{u}$ ($Q = -\frac{2}{3}$)
- proton udu & antiproton $\bar{u}\bar{d}\bar{u}$

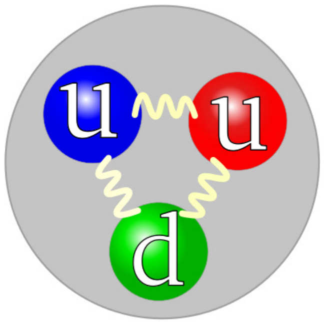
Matter *The first generation*

Almost all the matter in the universe is made up from just four of the fermions.

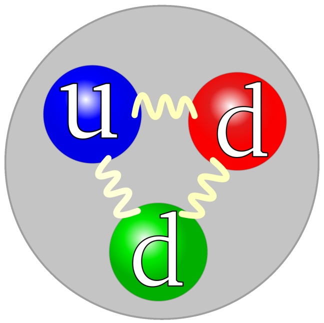
Particle	Symbol	Type	Charge [e]
Electron	e^-	lepton	-1
Neutrino	ν_e	lepton	0
Up quark	u	quark	$+\frac{2}{3}$
Down quark	d	quark	$-\frac{1}{3}$

The proton and neutron are simply the lowest energy bound states of a system of three quarks: essentially all an atomic or nuclear physicist needs.

Proton (p)



Neutron (n)



Matter *Three generations*

Nature is not so simple.
There are 3 generations/families of fundamental fermions (and only 3).

1^{st} generation		2^{nd} generation		3^{rd} generation	
Electron	e^-	Muon	μ^-	Tau	τ^-
Electron Neutrino	ν_e	Muon Neutrino	ν_μ	Tau Neutrino	ν_τ
Up quark	u	Charm quark	c	Top quark	t
Down quark	d	Strange quark	s	Bottom quark	b

- Each generation is a replica of (e^-, ν_e, u, d).
- The mass of the particles increases with each generation:
  the first generation is lightest and the third generation is the heaviest.
- The generations are distinct
  i.e. μ is not an excited e, or $\mu^- \to e^-\gamma$ would be allowed – this is not seen.
- There is a symmetry between the generations,
  but the origin of 3 generations is not understood!

Matter *Leptons*

Leptons are fermions which do not interact via the strong interaction.

Flavour	Charge [e]	Mass	Strong	Weak	EM
1^{st} generation					
e^-	-1	$0.511\ \mathrm{MeV}/c^2$	✗	✓	✓
ν_e	0	$< 2\ \mathrm{eV}/c^2$	✗	✓	✗
2^{nd} generation					
μ^-	-1	$105.7\ \mathrm{MeV}/c^2$	✗	✓	✓
ν_μ	0	$< 0.19\ \mathrm{MeV}/c^2$	✗	✓	✗
3^{rd} generation					
τ^-	-1	$1777.0\ \mathrm{MeV}/c^2$	✗	✓	✓
ν_τ	0	$< 18.2\ \mathrm{MeV}/c^2$	✗	✓	✗

- Spin $\frac{1}{2}$ fermions
- 6 distinct flavours
- 3 charged leptons: e^-, μ^-, τ^-.
  3 neutral leptons: ν_e, ν_μ, ν_τ.
- Antimatter particles $e^+, \bar{\nu}_e$ etc
- e is stable,
  μ and τ are unstable.

- Neutrinos are stable and almost massless. Only know limits on ν masses, but have measured mass differences to be $< 1\ \mathrm{eV}/c^2$. *Not completely true, see later...*
- Charged leptons experience only the electromagnetic & weak forces.
- Neutrinos experience only the weak force.

Matter *Quarks*

Quarks experience all the forces (strong, electromagnetic, weak).

Flavour	Charge [e]	Mass	Strong	Weak	EM
1^{st} generation					
u	$+\frac{2}{3}$	$2.3\ \mathrm{MeV}/c^2$	✓	✓	✓
d	$-\frac{1}{3}$	$4.8\ \mathrm{MeV}/c^2$	✓	✓	✓
2^{nd} generation					
c	$+\frac{2}{3}$	$1.3\ \mathrm{GeV}/c^2$	✓	✓	✓
s	$-\frac{1}{3}$	$95\ \mathrm{MeV}/c^2$	✓	✓	✓
3^{rd} generation					
t	$+\frac{2}{3}$	$173\ \mathrm{GeV}/c^2$	✓	✓	✓
b	$-\frac{1}{3}$	$4.7\ \mathrm{GeV}/c^2$	✓	✓	✓

- Spin $\frac{1}{2}$ fermions
- 6 distinct flavours
- Fractional charge:

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} +\frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$$

- Antiquarks $\bar{u}$, $\bar{d}$ etc
- Quarks are confined within hadrons, e.g. $p{=}(uud)$, $\pi^+{=}(u\bar{d})$

- Quarks come in three colours (colour charge) Red, Green, Blue.
  Colour is a label for the charge of the strong interaction.
  Unlike the electric charge ($+-$), the strong charge has three orthogonal colours (RGB).

Single, free quarks have never been observed. They are always confined in bound states called hadrons.
Macroscopically, hadrons behave as almost point-like composite particles.

Hadrons have two types:

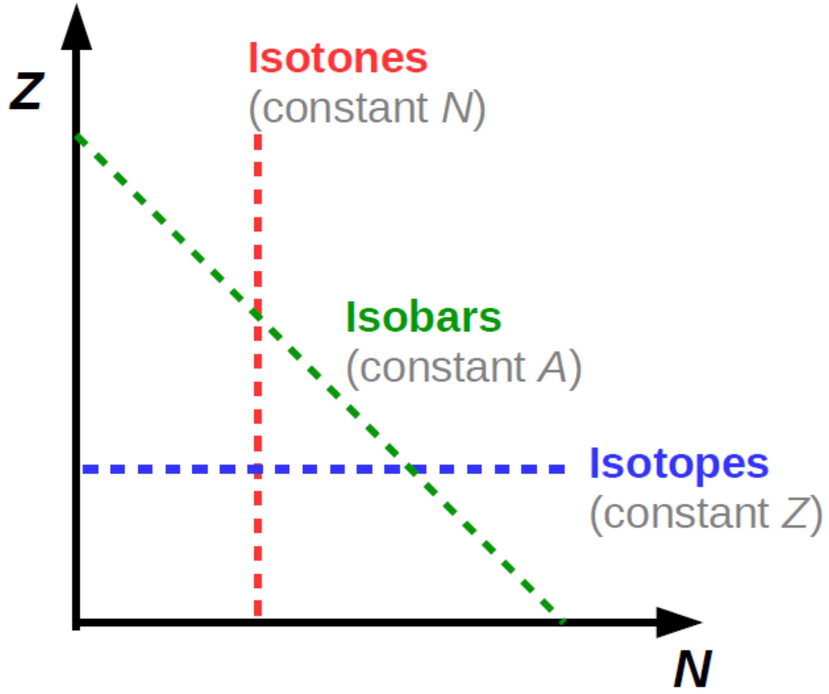
- **Mesons ($q\bar{q}$)**: Bound states of a quark and an antiquark.
  Mesons have integer spin 0, 1, 2... bosons.
  e.g. $\pi^+ \equiv (u\bar{d})$, charge $= (+\frac{2}{3} + +\frac{1}{3})e = +1e$
  $\pi^- \equiv (\bar{u}d)$, charge $= (-\frac{2}{3} + -\frac{1}{3})e = -1e$; antiparticle of π^+
  $\pi^0 \equiv (u\bar{u} - d\bar{d})/\sqrt{2}$, charge $= 0$; is its own antiparticle.

- **Baryons (qqq)**: Bound states of three quarks.
  Baryons have half-integer spin $\frac{1}{2}$, $\frac{3}{2}$... fermions.
  e.g. $p \equiv (udu)$, charge $= (+\frac{2}{3} + -\frac{1}{3} + +\frac{2}{3})e = +1e$
  $n \equiv (dud)$, charge $= (-\frac{1}{3} + +\frac{2}{3} + -\frac{1}{3})e = 0$
  Antibaryons e.g. $\bar{p} \equiv (\bar{u}\bar{d}\bar{u})$, $\bar{n} \equiv (\bar{d}\bar{u}\bar{d})$

A nucleus is a bound state of Z protons and N neutrons.
Protons and neutrons are generically referred to as nucleons.
A (mass number) $=$ Z (atomic number) $+$ N (neutron number).
A nuclide is a specific nucleus, characterised by Z, N.

Notation: Nuclide ^A_ZX.

e.g.	$^1_1$H or p:	$Z{=}1$,	$N{=}0$,	$A{=}1$
	$^2_1$H or d:	$Z{=}1$,	$N{=}1$,	$A{=}2$
	$^4_2$He or α:	$Z{=}2$,	$N{=}2$,	$A{=}4$
	$^{208}_{82}$Pb:	$Z{=}82$,	$N{=}126$,	$A{=}208$



In principle, antinuclei and antiatoms can be made from antiprotons, antineutrons and positrons – experimentally challenging!

Matter *The Periodic Table*

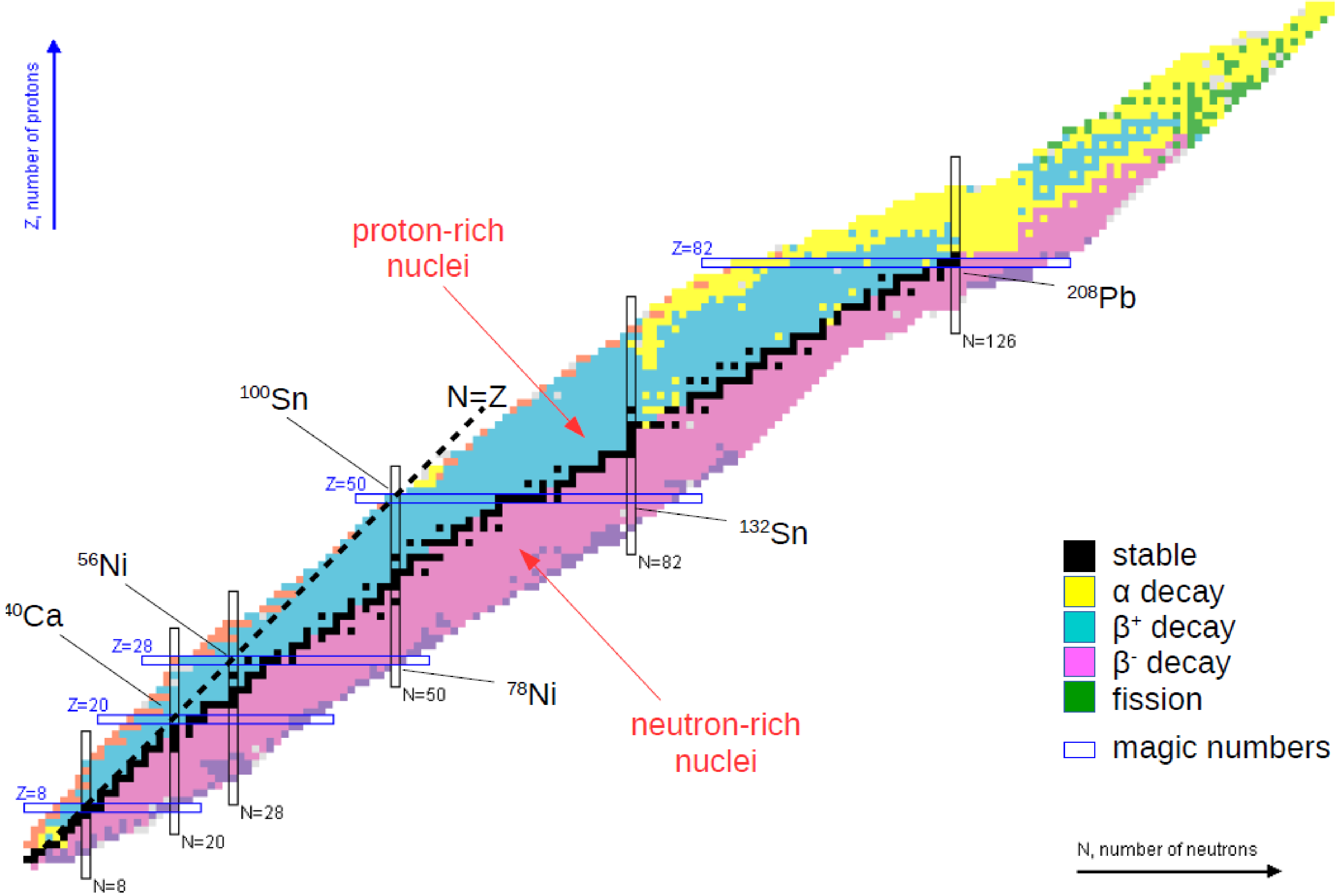
Periodic table classifies elements according to their chemical properties.

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
	*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
	**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Only hydrogen, helium and lithium were formed in the Big Bang.
All other elements are formed in stars.
Natural elements, H(Z=1) to U(Z=92).

Many more nuclides than elements.

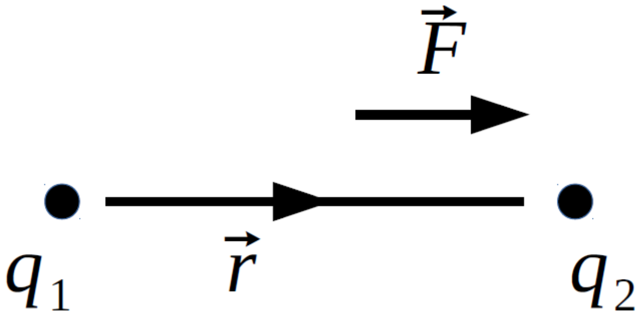
Colour coded according to decay mode.



Forces *Classical Picture*

A force is 'something' which pushes matter around and causes objects to change their motion.

In classical physics, the electromagnetic forces arise via action at a distance through the electric and magnetic fields, $\vec{E}$ and $\vec{B}$.



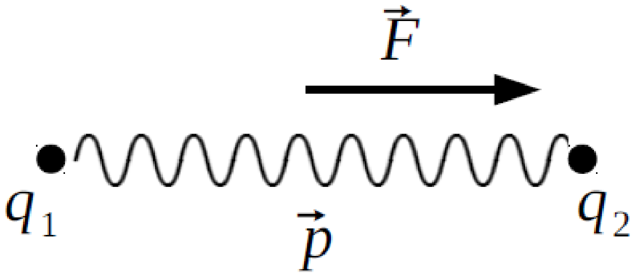
$$\vec{F} = \frac{q_1 q_2 \vec{r}}{r^2}$$

Newton: "...that one body should act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has, in philosophical matters, a competent faculty of thinking, can ever fall into it. Gravity must be caused by an agent, acting constantly according to certain laws, but whether this agent be material or immaterial, I leave to the consideration of my reader."

Forces *Quantum Mechanics*

Matter particles are quantised in QM, and the electromagnetic field should also be quantised (as photons).

Forces arise through the exchange of virtual field quanta called **Gauge Bosons**.



This process is called "second quantisation".

This process violates energy/momentum conservation *(more later)*.

However, this is permissible for sufficiently short times owing to the Uncertainty Principle

The exchanged particle is "virtual" – meaning it doesn't satisfy $E^2 = p^2c^2 + m^2c^4$.

Uncertainty principle: $\Delta E \Delta t \sim \hbar \quad \Rightarrow \quad$ range $R \sim c\Delta t \sim \hbar c/\Delta E$

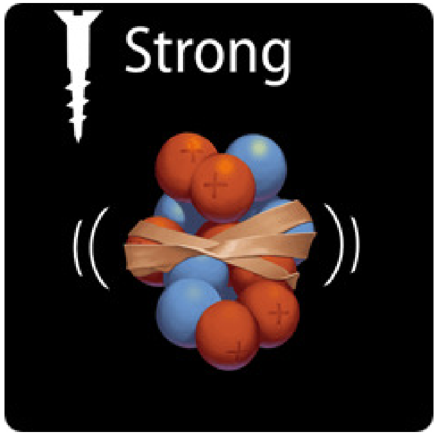
i.e. larger energy transfer (larger force) $\leftrightarrow$ smaller range.

Prob(emission of a quantum)$\propto q_1$, Prob(absorption of a quanta)$\propto q_2$

Coulomb's law can be regarded as the resultant effect of all virtual exchanges.

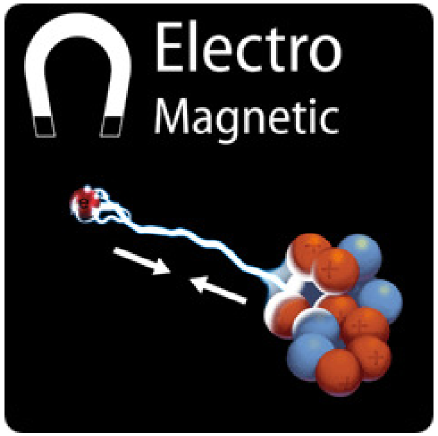
Forces *The four forces*

All known particle interactions can be explained by four fundamental forces.



Carried by the gluon. Holds atomic nuclei together.

Carried by the W and Z bosons. Responsible for radioactive decay.



Carried by the photon. Acts between charged particles.

Carried by the graviton. Acts between massive particles.

Forces *Gauge bosons*

Gauge bosons mediate the fundamental forces

- Spin 1 particles i.e. Vector Bosons
- Interact in a similar way with all fermion generations
- The exact way in which the Gauge Bosons interact with each type of lepton or quark determines the nature of the fundamental forces. This defines the Standard Model.

Force	Boson		Spin	Strength	Mass
Strong	8 gluons	g	1	1	massless
Electromagnetic	photon	γ	1	10^{-2}	massless
Weak	W and Z	W^+, W^-, Z	1	10^{-7}	80, 91 GeV
Gravity	graviton	?	2	10^{-39}	massless

- Gravity is not included in the Standard Model. The others are.

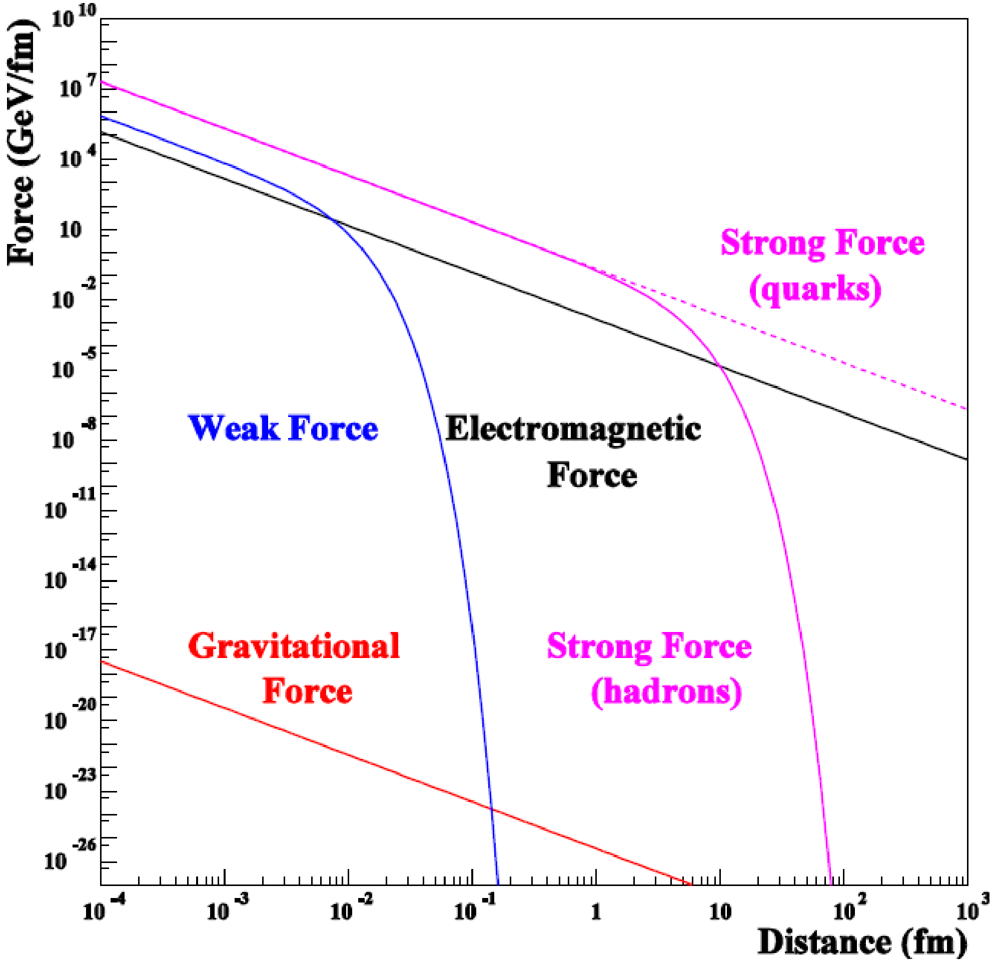
Forces *Range of forces*

The maximum range of a force is inversely related to the mass of the exchanged bosons.

$$\Delta E \Delta t \sim \hbar, \qquad E = mc^2$$

$$\Rightarrow mc^2 \sim \frac{\hbar}{\Delta t} \sim \frac{\hbar c}{r} \quad \Rightarrow r \sim \frac{\hbar}{mc}$$

Force	Range [m]
Strong	inf
Strong (nuclear)	10^{-15}
Electromagnetic	inf
Weak	10^{-18}
Gravity	inf



Due to quark confinement, nucleons start to experience the strong interaction at ∼2 fm.

Summary

- Particle vs nuclear physics
- Matter: generations, quarks, leptons, hadrons, nuclei
- Forces: classical vs QM, fundamental forces, gauge bosons, range

Problem Sheet: q.1

Up next...
Section 2: Kinematics, Decays and Reactions.

Glossary

- **Strong force** - force which binds quarks into hadrons; mediated by gluons.
- **Electromagnetic Force** - force between charged particles, mediated by photons.
- **Weak force** - force responsible for β-decay. Mediated by W and Z bosons.
- **Gauge boson** - particle which mediates a force.
- **Lepton** - fermion which does not feel the strong interaction.
- **Neutrino** - uncharged lepton which experiences only weak interactions.
- **Quark** - fundamental fermion which experiences all forces.
- **Hadron** - bound state of quarks and/or antiquarks.
- **Baryon** - hadron formed from three quarks.
- **Meson** - hadron formed from quark+antiquark.
- **Generations/Families** - three replicas of the fundamental fermions.
- **Nucleus** - massive bound state of neutrons and protons at centre of an atom.
- **Strong nuclear force** - strong force between nucleons which binds atomic nucleus. Mediated by mesons, such as the pion.
- **Nucleon** - proton or neutron.
- **Nuclide** - specific nuclear species with N neutrons and Z protons.
- **Mass number** - total number of nucleons in nucleus, A.
- **Atomic Number** - number of protons in nucleus, Z.
- **Neutron Number** - number of neutrons in nucleus, N.
- **Isobars** - nuclides with the same Mass Number A.
- **Isotopes** - nuclides with the same Atomic Number Z.
- **Isotones** - nuclides with the same Neutron Number N.