1. Introduction
Particle and Nuclear Physics

Prof. Tina Potter

UNIVERSITY OF CAMBRIDGE
In this section...

- Course content
- Practical information
- Matter
- Forces
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
www.hep.phy.cam.ac.uk/~chpotter/particleandnuclearphysics/mainpage.html

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: before/after lectures, via email (cp594@cam.ac.uk), in-person chats are always welcome

Prof. Tina Potter
1. Introduction
Atom

**Binding energy ~ Rydberg ~ 10 eV**

Electrons bound to atoms by EM force

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

Nucleus

**Binding energy ~ 10 MeV/nucleon**

Nuclei held together by strong “nuclear” force

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

Nucleon

**Binding energy ~ 1 GeV**

Protons & neutrons held together by the strong force

- Size: $p, n \sim 1 \text{fm}$
- Charge: proton $+e$, neutron is neutral
- Mass: $p, n = 939.57 \text{ MeV}/c^2 \sim 1836 m_e$
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 $\bar{u}\bar{d}\bar{u}$
Almost all the matter in the universe is made up from just four of the fermions.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Type</th>
<th>Charge [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>e$^-$</td>
<td>lepton</td>
<td>$-1$</td>
</tr>
<tr>
<td>Neutrino</td>
<td>$\nu_e$</td>
<td>lepton</td>
<td>$0$</td>
</tr>
<tr>
<td>Up quark</td>
<td>$u$</td>
<td>quark</td>
<td>$+\frac{2}{3}$</td>
</tr>
<tr>
<td>Down quark</td>
<td>$d$</td>
<td>quark</td>
<td>$-\frac{1}{3}$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>1st generation</th>
<th>2nd generation</th>
<th>3rd generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>Muon</td>
<td>Tau</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
<td>$\nu_\tau$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>$\mu^-$</td>
<td>$\tau^-$</td>
</tr>
<tr>
<td>Up quark</td>
<td>Charm quark</td>
<td>Top quark</td>
</tr>
<tr>
<td>$u$</td>
<td>$c$</td>
<td>$t$</td>
</tr>
<tr>
<td>Down quark</td>
<td>Strange quark</td>
<td>Bottom quark</td>
</tr>
<tr>
<td>$d$</td>
<td>$s$</td>
<td>$b$</td>
</tr>
</tbody>
</table>

- Each generation is a replica of $(e^-, \nu_e, u, d)$.
- 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. $\mu$ is not an excited $e$, or $\mu^- \rightarrow e^- \gamma$ would be allowed – this is not seen.
- There is a symmetry between the generations,
  but the origin of 3 generations is not understood!
Leptons are fermions which do not interact via the strong interaction.

<table>
<thead>
<tr>
<th>Flavour</th>
<th>Charge [e]</th>
<th>Mass</th>
<th>Strong</th>
<th>Weak</th>
<th>EM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^-$</td>
<td>$-1$</td>
<td>0.511 MeV/c$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$0$</td>
<td>$&lt; 2$ eV/c$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2\textsuperscript{nd} generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>$-1$</td>
<td>105.7 MeV/c$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$0$</td>
<td>$&lt; 0.19$ MeV/c$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3\textsuperscript{rd} generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau^-$</td>
<td>$-1$</td>
<td>1777.0 MeV/c$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>$0$</td>
<td>$&lt; 18.2$ MeV/c$^2$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- Spin $\frac{1}{2}$ fermions
- 6 distinct flavours
- 3 charged leptons: $e^-$, $\mu^-$, $\tau^-$. 3 neutral leptons: $\nu_e$, $\nu_\mu$, $\nu_\tau$.
- Antimatter particles $e^+$, $\bar{\nu}_e$ etc
- $e$ is stable, $\mu$ and $\tau$ are unstable.

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

Prof. Tina Potter

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

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

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

\[
\left( \begin{array}{c}
  u \\
  c \\
  s \\
  t \\
\end{array} \right) \left( \begin{array}{c}
  +\frac{2}{3} \\
  1.3 \text{ GeV/c}^2 \\
  -\frac{1}{3} \\
  95 \text{ MeV/c}^2 \\
\end{array} \right)
\]

- 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).
Matter  Hadrons

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 \(0, 1, 2\ldots\) 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 \(\pi^+\)
  \(\pi^0 \equiv (u\bar{u} - d\bar{d})/\sqrt{2}\), charge = 0; is its own antiparticle.

- **Baryons** \((qqq)\): Bound states of three quarks. Baryons have half-integer spin \(\frac{1}{2}, \frac{3}{2}\ldots\) 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. \(\bar{p} \equiv (\bar{u}\bar{d}\bar{u})\), \(\bar{n} \equiv (\bar{d}\bar{u}\bar{d})\)
Matter  

Nuclei

A nucleus is a bound state of \( Z \) protons and \( N \) neutrons. Protons and neutrons are generically referred to as nucleons. 

\[ A \text{ (mass number)} = Z \text{ (atomic number)} + N \text{ (neutron number)}. \]

A nuclide is a specific nucleus, characterised by \( Z, N \).

**Notation: Nuclide** \( \frac{A}{Z} X \).

- \( ^1_1 H \) or \( p \): \( Z=1, \; N=0, \; A=1 \)
- \( ^2_1 H \) or \( d \): \( Z=1, \; N=1, \; A=2 \)
- \( ^4_2 He \) or \( \alpha \): \( Z=2, \; N=2, \; A=4 \)
- \( ^{208}_{82} Pb \): \( Z=82, \; N=126, \; A=208 \)

In principle, antinuclei and antiatoms can be made from antiprotons, antineutrons and positrons – experimentally challenging!
Only hydrogen, helium and lithium were formed in the Big Bang. All other elements are formed in stars. Natural elements, $\text{H}(Z=1)$ to $\text{U}(Z=92)$.
Many more nuclides than elements.

Colour coded according to decay mode.
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.”
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**. 

\[
\begin{array}{c}
\bullet \\
q_1
\end{array} \xrightarrow{\vec{F}} \begin{array}{c}
\bullet \\
q_2
\end{array} \begin{array}{c}
\vec{p}
\end{array} 
\]

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

\[ E^2 = p^2 c^2 + m^2 c^4. \]

Uncertainty principle: \[ \Delta E \Delta t \sim \hbar \Rightarrow \text{range } R \sim c \Delta t \sim \hbar c / \Delta E \]

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

\[ \text{Prob(} \text{emission of a quantum} \text{)} \propto q_1, \quad \text{Prob(} \text{absorption of a quanta} \text{)} \propto q_2 \]

Coulomb’s law can be regarded as the resultant effect of all virtual exchanges.
All known particle interactions can be explained by four fundamental forces.

**Strong**
Carried by the gluon. Holds atomic nuclei together.

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

**Electro Magnetic**
Carried by the photon. Acts between charged particles.

**Gravity**
Carried by the graviton. Acts between massive particles.
**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.

<table>
<thead>
<tr>
<th>Force</th>
<th>Boson</th>
<th>Spin</th>
<th>Strength</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>8 gluons</td>
<td>1</td>
<td>1</td>
<td>massless</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photon</td>
<td>$\gamma$</td>
<td>1</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Weak</td>
<td>$W$ and $Z$</td>
<td>$W^+, W^-$, $Z$</td>
<td>1</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>graviton</td>
<td>?</td>
<td>$10^{-39}$</td>
<td>massless</td>
</tr>
</tbody>
</table>

- 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.

\[ \Delta E \Delta t \sim \hbar, \quad E = mc^2 \]

\[ \Rightarrow mc^2 \sim \frac{\hbar}{\Delta t} \sim \frac{\hbar c}{r} \Rightarrow r \sim \frac{\hbar}{mc} \]

<table>
<thead>
<tr>
<th>Force</th>
<th>Range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>inf</td>
</tr>
<tr>
<td>Strong (nuclear)</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>inf</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>inf</td>
</tr>
</tbody>
</table>

Due to quark confinement, nucleons start to experience the strong interaction at $\sim 2$ fm.

Prof. Tina Potter 1. Introduction
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 $\beta$-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 $N$. 