Particle and Nuclear Physics

Lent/Easter Terms 2009

Chris Lester and David Ward

Section I

Matter and Forces

Introduction

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

NUCLEAR PHYSICS is the study of

MATTER: Complex nuclei
(protons and neutrons)

FORCES: Strong "Nuclear" Force
(underlying strong force)
+weak + e/m in decays

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

Many models of Nuclear Physics.

PARTICLE PHYSICS is the study of

MATTER: Elementary particles

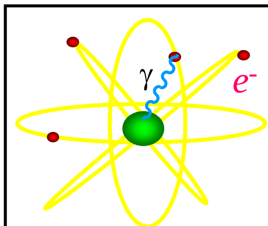
FORCES: Basic forces in nature

Electroweak { Electromagnetic, Weak }
Strong

Current understanding embodied in
THE STANDARD MODEL
which successfully describes all current data (but not including gravity)

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

3

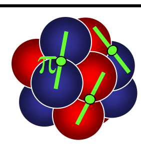


ATOM

Electrons bound to atom by electromagnetic force

Binding energy ~Rydberg~10 eV

Size: Atom ~10^{-10} m, e^- < 10^{-19}m
Charge: Atom is neutral, electron –e
Mass: Atom mass ~ in nucleus, m_e= 0.511 MeV/c^2
Chemical properties depend on Atomic Number, Z.



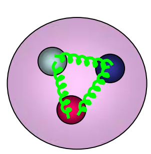
NUCLEUS

Nuclei held together by strong "nuclear" force

Binding energy ~10 MeV/nucleon

Size: Nucleus (medium A) ~ 5fm

1fm = 10^{-15}m



NUCLEON

Protons and neutrons: held together by the strong force

Binding energy ~1 GeV

Size: p, n ~ 1fm
Charge: proton $+e$; neutron uncharged
Mass : p, n = 939.57 MeV/c^2 ~ 1836 m_e

4

Matter

We now know that all matter is made of two types of elementary particles (spin ½ fermions):

LEPTONS: e.g. e^-, ν_e

QUARKS: e.g. up quark (u) and down quark (d)
proton (uud), neutron (udd)

A consequence of relativity and quantum mechanics (Dirac equation) is that for every particle there exists an antiparticle which has identical mass, spin, energy, momentum, BUT has the opposite sign of interaction (e.g. electric charge).

ANTIPARTICLES: e.g. positron e^+ , antiquarks ($\bar{u}$, $\bar{d}$),
antiproton ($\bar{u}\bar{u}\bar{d}$)

5

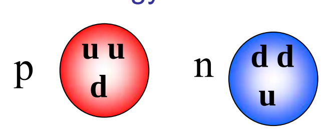
Matter: 1st Generation

Almost all the phenomena you will have encountered so far can be described by the interactions of FOUR spin ½ particles:

THE FIRST GENERATION

Particle	Symbol	Type	Charge Units of e
Electron	e^-	Lepton	-1
Neutrino	ν_e	Lepton	0
Up Quark	u	Quark	+⅔
Down Quark	d	Quark	-⅓

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.



6

Matter: 3 Generations

Nature turns out not to be quite so simple. There are actually THREE "generations" (or "families") of fundamental fermions:

1st Generation		2nd Generation		3rd 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 e.g. (μ^-, ν_μ, c, s) is a replica of (e^-, ν_e, u, d)
- The main difference is the mass of the particles: the 1st generation are the lightest and the 3rd generation are heaviest.
- The generations are definitely distinct – μ is not just an excited electron etc.
- Obvious symmetry, but origin of 3 generations is **NOT UNDERSTOOD**.

7

Leptons

Particles which DO NOT INTERACT via the STRONG interaction.

- Spin ½ fermions
- 6 distinct "FLAVOURS"
- 3 charged leptons: e^-, μ^-, τ^-
  μ and τ unstable
- 3 neutral leptons: ν_e, ν_μ, ν_τ
  Neutrinos are stable and (almost?) massless. Only have limits on their masses, but estimates of mass differences are less than 1 eV/c². Assumed massless in Standard Model.

Gen.	Flavour	Charge /e	Approx. Mass
1st	e^-	-1	0.511 MeV/c²
	ν_e	0	<2 eV/c²
2nd	μ^-	-1	105.7 MeV/c²
	ν_μ	0	<0.19 MeV/c²
3rd	τ^-	-1	1777.0 MeV/c²
	ν_τ	0	<18.2 MeV/c²

- Also antimatter partners, e^+, $\bar{\nu}_e$ etc.
- Charged leptons only experience the electromagnetic and weak forces
- Neutrinos only experience the weak force

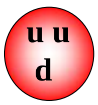
8

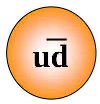
Quarks

Quarks experience ALL the forces (electromagnetic, strong, weak)

- Spin ½ fermions
- Fractional charge
- 6 distinct "flavours"
- Quarks come in 3 "colours"
  Red, Green, Blue
- Quarks are confined within HADRONS

e.g. $p \equiv (uud)$ $\pi^+ \equiv (u\bar{d})$





Gen.	Flavour	Charge /e	Approx. Mass (GeV/c²)
1st	u	+⅔	0.35
	d	-⅓	0.35
2nd	c	+ ⅔	1.5
	s	- ⅓	0.5
3rd	t	+ ⅔	174
	b	- ⅓	4.5

+antiquarks $\bar{u}, \bar{d}$ etc.

COLOUR is just a label for the charge of the strong interaction. Unlike the electric charge of an electron (*-e*), the strong charge comes in three orthogonal colours RGB.

Hadrons

- Single free quarks are NEVER observed, but are always CONFINED in bound states, called HADRONS.
- Macroscopically hadrons behave as almost point-like COMPOSITE particles.

Hadrons are of two types:

MESONS $(q\bar{q})$

Bound states of a QUARK and an ANTIQUARK

All have INTEGER spin 0, 1, 2,… Bosons

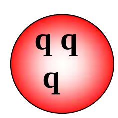
e.g. $\pi^+ \equiv (u\bar{d})$ charge = $(+2/3 + 1/3)e = +1e$

$\pi^- \equiv (\bar{u}d)$ charge = $(-2/3 - 1/3)e = -1e$; antiparticle of π^+

$\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ charge=0; is its own antiparticle

BARYONS (qqq)

Bound states of 3 QUARKS

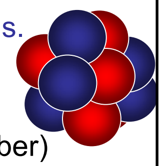


All have HALF-INTEGER spin 1/2, 3/2,… Fermions

e.g. $p \equiv (uud)$ $n \equiv (udd)$

PLUS ANTIBARYONS $(\bar{q}\bar{q}\bar{q})$ e.g. $\bar{p} \equiv (\bar{u}\bar{u}\bar{d})$ $\bar{n} \equiv (\bar{u}\bar{d}\bar{d})$

Nuclei

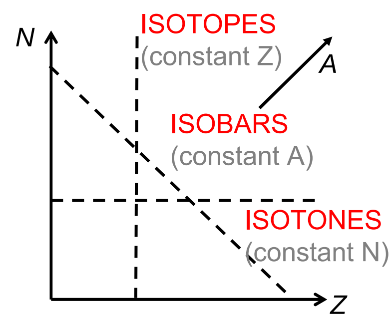


- A NUCLEUS is a bound state of *Z* protons and *N* neutrons.
- p and n are generically referred to as "NUCLEONs"
- *A* (mass number) = *Z* (atomic number) + *N* (neutron number)
- A "NUCLIDE" is a specific nucleus characterised by *Z, N*

Notation: Nuclide $^{A}_{Z}\mathrm{X}$

e.g.

$^{1}_{1}\mathrm{H}$ or p	$Z=1,$	$N=0,$	$A=1$
$^{2}_{1}\mathrm{H}$ or d	$Z=1,$	$N=1,$	$A=2$
$^{4}_{2}\mathrm{He}$ or α	$Z=2,$	$N=2,$	$A=4$
$^{208}_{82}\mathrm{Pb}$	$Z=82,$	$N=126,$	$A=208$

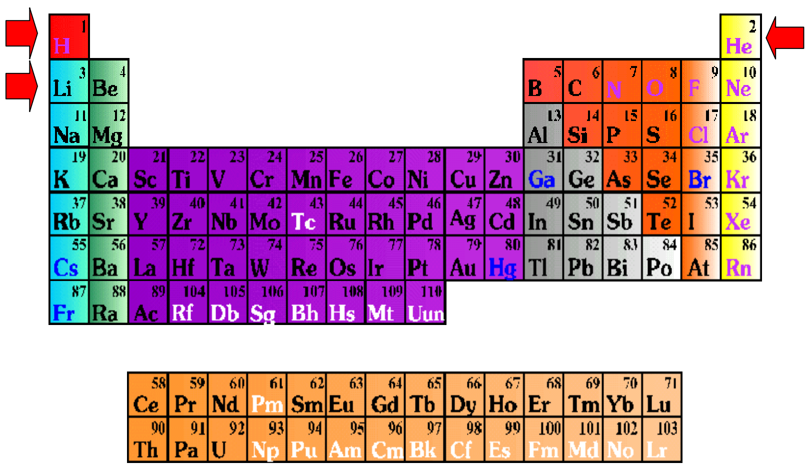


In principle, ANTINUCLEI and antiatoms can be made from antiprotons, antineutrons and positrons. Experimentally challenging, < 100 antihydrogen atoms made.

11

The Periodic Table

Only THREE elements are formed in the Big Bang.
ALL other elements are formed in stars.



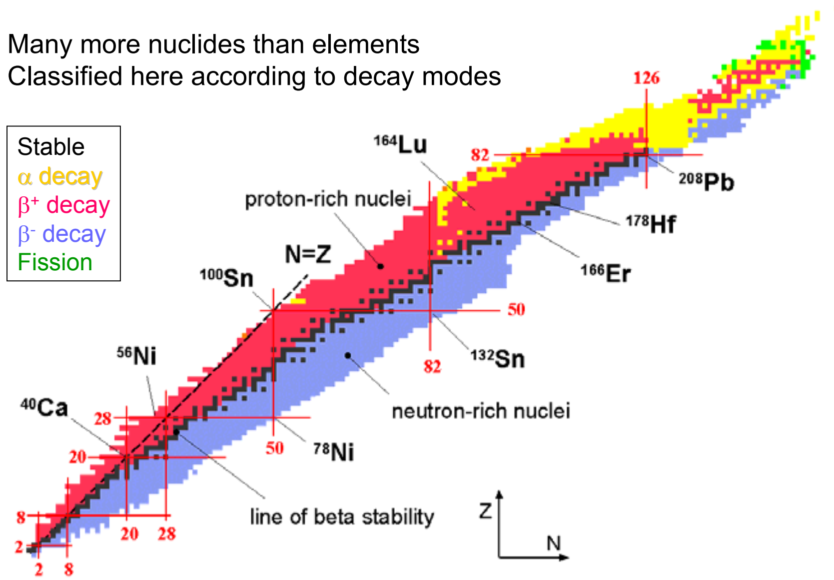
Natural elements : H (Z=1) to U (Z=92)

Periodic table classifies elements according to their chemical properties.

12

Chart of the nuclides

Many more nuclides than elements
Classified here according to decay modes

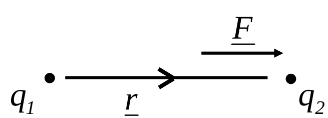


13

Forces

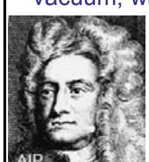
Classical Picture: A force is "something" which pushes matter around and causes objects to change their motion (Newton II).

e.g. classically, electromagnetic forces arise via action at a distance through the electric and magnetic fields, $\underline{E}$ and $\underline{B}$



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

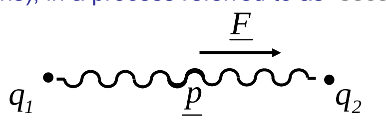
Newton: "…that one body should act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has, in philosophical matters, a competent faculty of 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."



14

Forces

Quantum Mechanically: As well as the matter particles, the electromagnetic field should be quantised (as photons). Forces arise due to exchange of VIRTUAL FIELD QUANTA (Gauge Bosons), in a process referred to as "second quantization".



This process violates energy/momentum conservation. But this is OK for sufficiently short times owing to the Uncertainty Principle.

Exchanged particle is called "virtual"

$$\Delta E\ \Delta t \sim \hbar \quad \Rightarrow \quad \text{range} \quad R \sim c\Delta t \sim \hbar c/\Delta E$$

i.e. larger energy transfer (larger force) ↔ smaller range

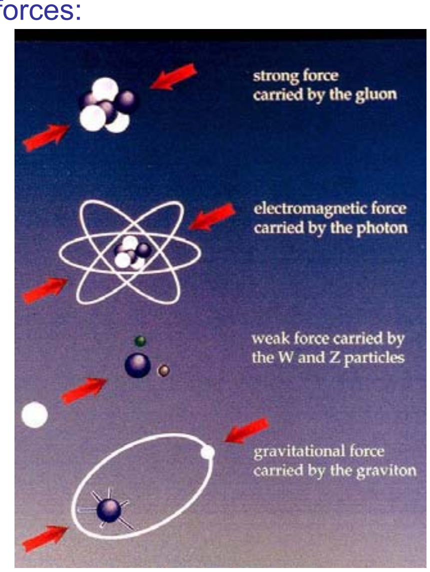
Probability of emission of a quantum $\propto q_1$ and probability of absorption $\propto q_2$, and vice versa

Coulomb's law is the resultant effect of all virtual exchanges.

15

Forces

All (known) particle interactions can be explained by 4 fundamental forces:



STRONG

ELECTROMAGNETIC

Unified as Electroweak

WEAK

GRAVITY

16

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 the leptons and quarks determines the nature of the fundamental forces.

Force	Boson		Spin	Strength (relative)	Mass (GeV/c^2)
Strong	8 gluons	g	1	1	Massless
Electromagnetic	Photon	γ	1	10^{-2}	Massless
Weak	W and Z	$W^{\pm}, Z^0$	1	10^{-7}	80, 91
Gravity	Graviton	?	2	10^{-39}	Massless

17

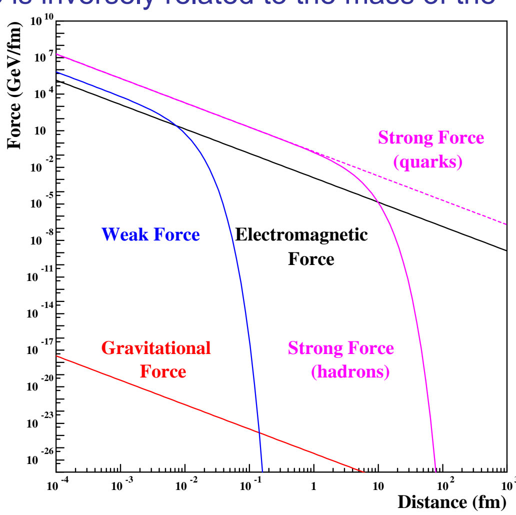
Range of Forces

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

$$\Delta E \Delta t \sim \hbar \quad ; \quad E = mc^2$$

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

Force	Range (m)
Strong	∞
Strong (Nuclear)	10^{-15}
Electromagnetic	∞
Weak	10^{-18}
Gravity	∞



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

18

How do we study particles and forces ?

- Static Properties (i.e. what particles/states exist?)
  Mass, spin and parity (J^P), magnetic moments, bound states
- Particle Decays (most particles and many nuclei are unstable)
  Allowed/forbidden decays → Conservation Laws (selection rules)
- Particle Scattering
  Direct production of new massive particles, e.g. in matter/antimatter ANNIHILATION
  High energy ⇒ study forces at short distances
  Study of particle interaction cross-sections.

Force	Typical Lifetime (s)	Typical Cross-section (mb)
Strong	10^{-23}	10
Electromagnetic	10^{-20}	10^{-2}
Weak	10^{-8}	10^{-13}

19

Glossary of terms

- **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

20

Glossary of terms (contd.)

- **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