Nuclear & Particle Physics
Junior Honours

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Course web page:

http://www.ph.ed.ac.uk/~muheim/teaching/np3

Recommended Textbooks:

Simple

- Particle Physics – B.R. Martin & G. Shaw, 2nd edition (Wiley 1997)
- Introduction to High Energy Physics - D.H. Perkins, 4th edition (CUP 2000)
- Introduction to Elementary Particles - D. Griffiths (Wiley 1987)
- Quarks and Leptons – F. Halzen & A.D. Martin (Wiley 1984)
- Review of Particles Physics http://durpdg.dur.ac.uk/lbl

Advanced

Particle Physics Course Outline

- Introduction & Fundamental Particles
  - Quarks and Leptons, Photons
  - Natural Units, Kinematics
- Feynman diagrams
  - Antiparticles
  - Electromagnetic Interaction
- Interaction with Matter
  - Particle Detectors, Accelerators, Experiments
- Quarks
  - Meson and Baryons
  - Isospin, Strangeness
- Strong Interaction
  - Colour, Gluons
  - Confinement, running coupling constants
- Symmetries & Conservation Laws
  - Baryon/lepton number, charge and parity
- Weak Interaction
  - Muon and tau decay
  - Heavy quarks, CKM mechanism
- Neutrinos
  - Neutrino Mass and Oscillations
- Electroweak Theory
  - W and Z bosons, LEP
  - Spontaneous Symmetry Breaking, Higgs

Motivation

What's the interest in Particle Physics?

Human quest for knowledge

Relation to cosmology (matter vs antimatter, dark matter, dark energy)

"Journey to the centre of the Universe" - F Close

Technology - CERN

The world's largest particle physics laboratory

... where the web was born!

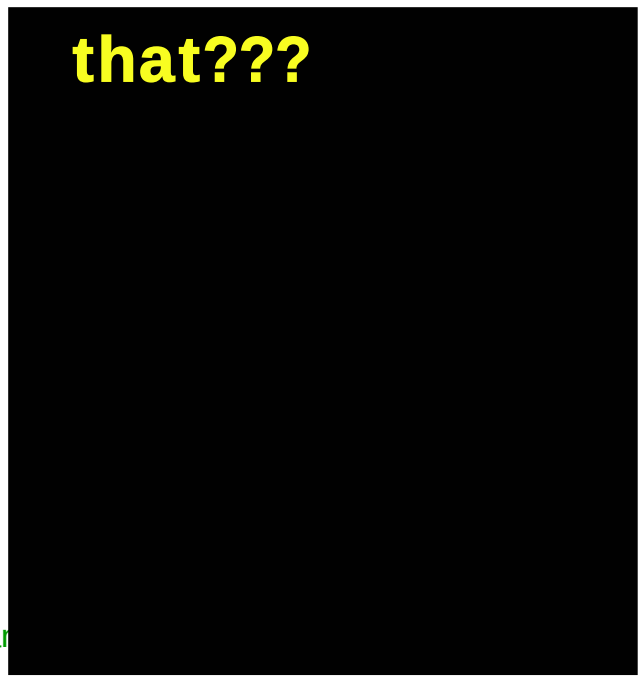
Material science, e.g. μSR, Medical, e.g. PET

Big Bang:

Matter and Antimatter were created in equal amounts

Why does the Universe look like

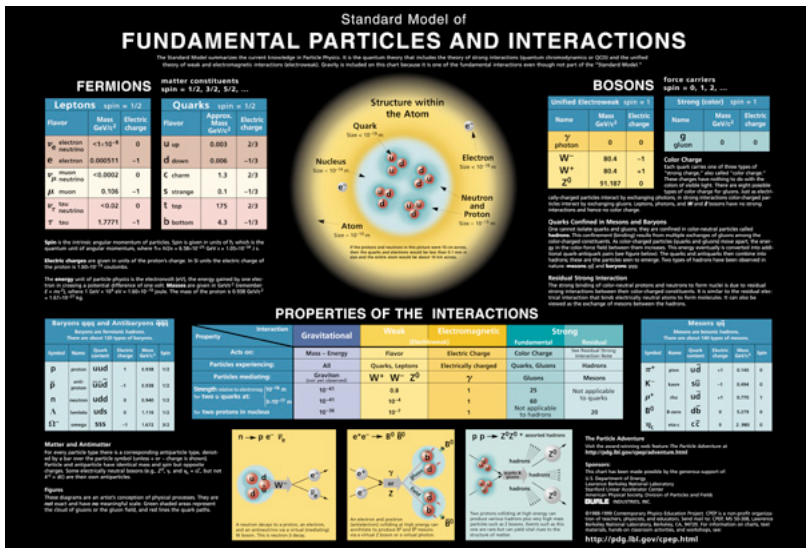
not



Particle Physics Education Sites

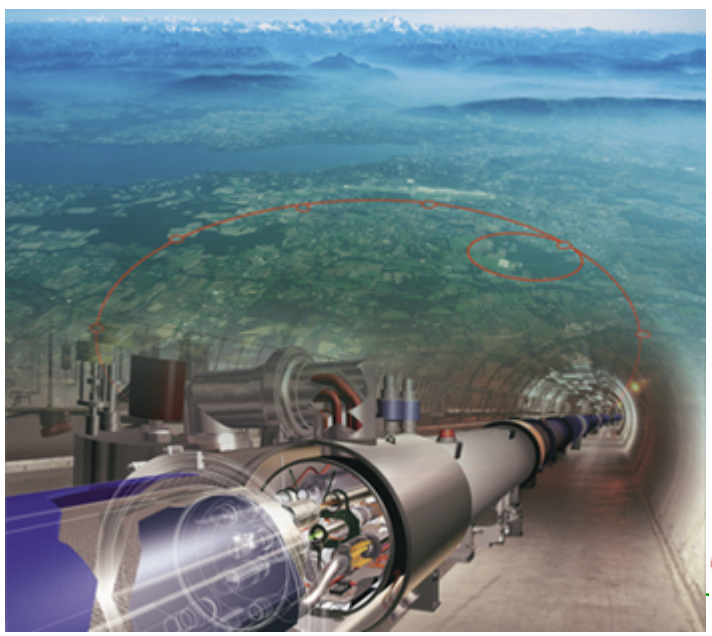
http://particleadventure.org/particleadventure/

http://www.cpepweb.org/particles.html



http://www2.slac.stanford.edu/vvc/Default.htm

http://public.web.cern.ch/public/



The Questions of Particle Physics

What is matter made of?

Greeks: earth, air, water, fire

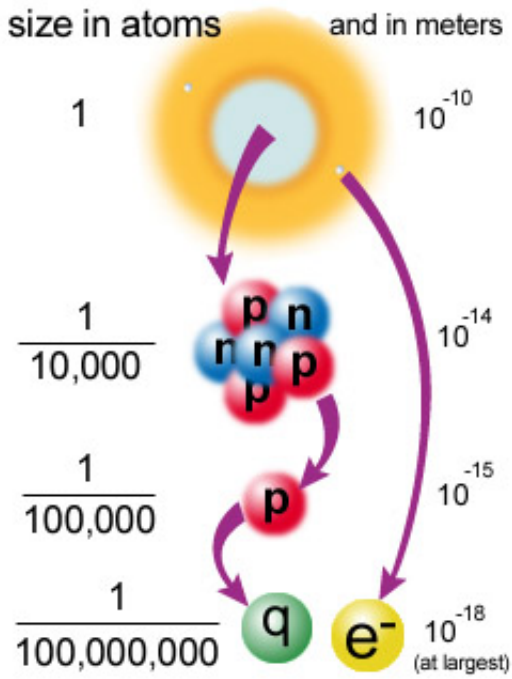
atomos (ατομοσ)

Atoms

Nucleus & electrons

Protons, neutrons

Particle Physics Quarks and electrons



How do these particles interact?

What are electromagnetic forces?

What holds nucleus together?

What causes radioactivity?

How does gravity act at such large distances?

Standard Model of Particle Physics

"A Briefest Introduction"

Particle Physics

Study of Nature at shortest distance and times

Matter

Fundamental constituents of Universe - elementary particles

Forces

Basic forces of Nature – interactions between elementary particles

Aim to find simplest classification of fundamental particles and their interactions

Matter

Two types of fermions - spin $\frac{1}{2}$

Leptons: e-, ν

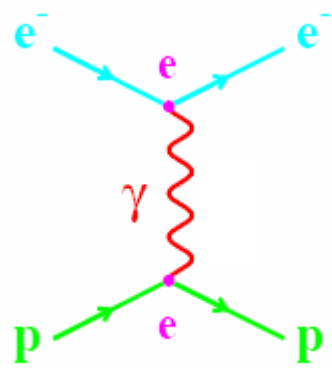
Quarks: u, d proton = (uud)

Antimatter: positron (e+), antiproton

Forces

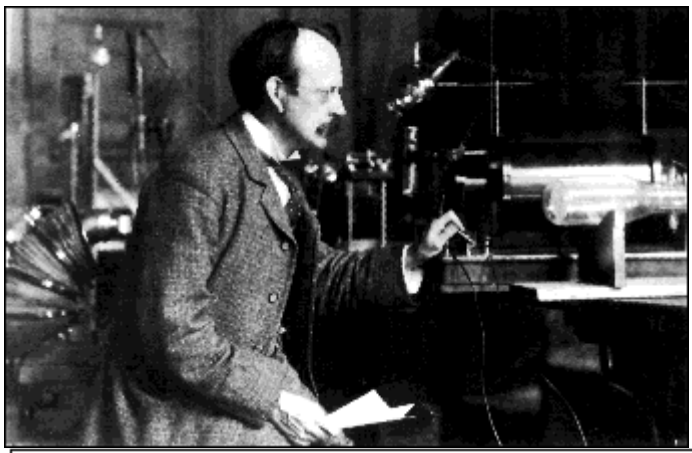
Interactions between quarks and leptons are mediated by exchange of gauge bosons – spin 1

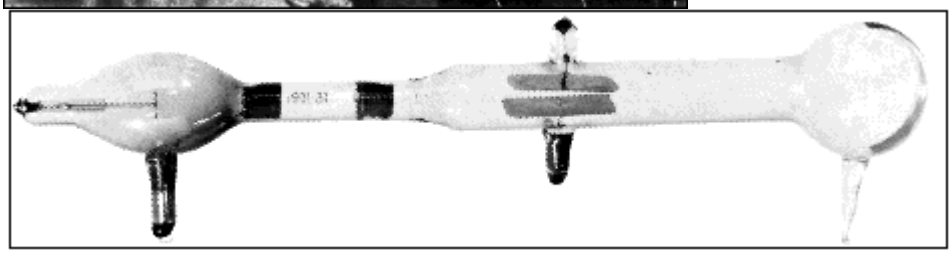
Electromagnetic	photons
Strong	gluons
Weak	W and Z
Gravity	graviton



The Electron

Discovered in 1897 by J.J. Thomson





Electron - Elementary Particle

Point-like: size < 10^{-6} fm (10^{-21} m)

Stable: lifetime > 4.6 10^{26} yrs

Electric charge

$q_e = -e = -1.60217653(14) \cdot 10^{-19}$ C

Mass

$m_e = 0.510998918(44)$ MeV $= 9.11 \cdot 10^{-31}$ kg

Spin

Intrinsic property: spin $\frac{1}{2}$

Fermion, satisfies Pauli Exclusion Principle

The Photon

Discovered in 1924 by A.H. Compton

Photon - Elementary Particle

Pointlike: size < 10^{-6} fm (10^{-21} m)

Stable:

Electric charge

No charge: $q_\gamma < = 5 \cdot 10^{-30}$ e

Mass

Mass-less: $m_\gamma < 6 \cdot 10^{-17}$ eV

Energy

$E = h\nu = hc/\lambda$

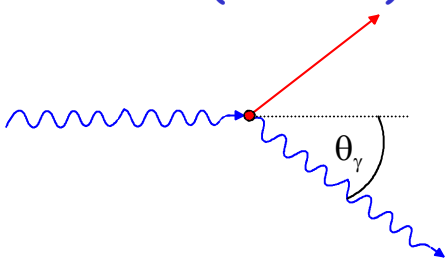
Spin

Intrinsic property: spin 1

Boson, satisfies Bose-Einstein statistics

Compton effect

Photon scatters off electron (at rest)



$$\gamma + e \rightarrow \gamma' + e'$$

Energy and momentum conservation

$E + m_e = E' + E_e$ (Lab frame)

$E = E'\cos\theta + p_e \cos\theta_e$

$E'\sin\theta = p_e \sin\theta_e$

Eliminate p_e, E_e, θ_e

$$E' = E \frac{1}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

$$\lambda' = \lambda + \lambda_c(1 - \cos\theta)$$

where $\lambda_c = \frac{\hbar}{m_e c} = 3.86 \cdot 10^{-13} m$

Compton wavelength

Elementary Particles

"What you already know"

" Explain almost all of Atomic & Nuclear Physics"

Constituents of Matter:

Four spin $\frac{1}{2}$ particles - fermions

Particle	symbol	charge	type
Electron	e-	-1	lepton
Neutrino	ν_e	0	lepton
Up-quark	u	+2/3	quark
Down-quark	d	-1/3	quark

Leptons

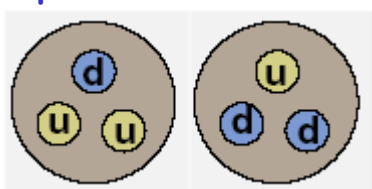
Electron and neutrino

Quarks

Nucleons are composite 3-quark states

proton (uud)

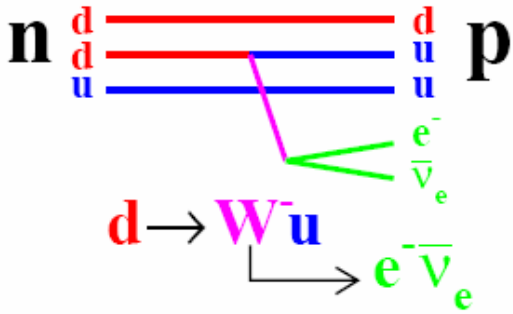
neutron (udd)



Example - Beta decay:

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

$$d \rightarrow u + e^- + \bar{\nu}_e$$



Generations of Quarks and Leptons

Nature replicates itself

is not that simple

3 generations of fundamental fermions

First Generation		2nd Generation		3rd Generation		Charge e
Electron Neutrino	ν_e	Muon neutrino	ν_μ	Tau neutrino	ν_τ	0
Electron	e-	Muon	μ-	Tau	τ-	-1
Up quark	u	Charm quark	c	Top quark	t	+2/3
Down quark	d	Strange quark	s	Bottom quark	b	-1/3

Ordinary Matter

built from 1st generation

Lepton (ν_e, e-) and quark (u,d) doublet

Higher generations

copies of (ν_e, e-, u, d)

Undergo identical interactions

Only difference in mass of particles

higher generations are heavier

Why 3 generations?

Symmetry/structure not understood!

Leptons

Particles that do not interact via strong force

6 distinct flavours

Electron and **Electron Neutrino** partners

fermions - spin $\frac{1}{2}$

Additive quantum numbers - Charge q,

Lepton family number L_e, L_μ, L_τ

Muon

Like electrons, but 200 times heavier

"Who ordered that?" I.I. Rabi

Unstable – Lifetime: 2.2 μs

Separate **Muon Neutrino** partner

Tau

Even heavier - m_e x 3500

Unstable – Lifetime: 291 fs

Partner is **Tau Neutrino**

Lepton	Symbol	Charge	Mass	Lepton Family Number		
		e	MeV/c^2	L_e	L_μ	L_τ
Electron Neutrino	ν_e	0	$< 3 \times 10^{-6}$	+1	0	0
Electron	e^-	-1	0.511	+1	0	0
Muon Neutrino	ν_μ	0	< 0.19	0	+1	0
Muon	μ^-	-1	105.66	0	+1	0
Tau Neutrino	ν_τ	0	< 18	0	0	+1
Tau	τ^-	-1	1777	0	0	+1

Lepton Properties

Antiparticles

lepton ⟷ antilepton partner

with equal mass, but opposite charge

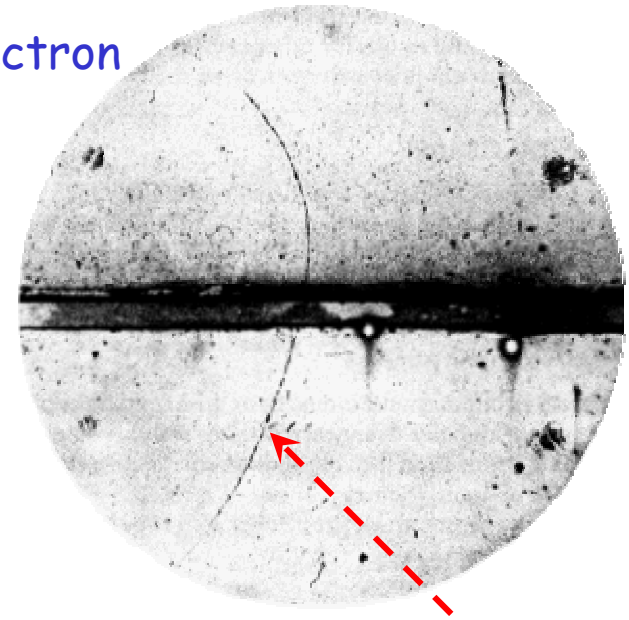
opposite additive quantum numbers

Example:

Positron (e+) or anti-electron

discovered in 1931

by Anderson



Positron track

Lepton family number

L_e, L_μ, L_τ are conserved in all reactions

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \quad \text{allowed}$$

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \quad \text{allowed}$$

$$\mu^+ \to e^+ \gamma \quad \text{forbidden}$$

$$\mu^+ \to e^+ e^- e^+ \quad \text{forbidden}$$

Charged Leptons: e-, μ-, τ-

Interact via electromagnetic and weak force

Neutrinos

Interact only via weak force

almost massless - Neutrino oscillations

ν_e and anti-ν_e are different particles

Quarks

Quark Properties

Fermions - spin $\frac{1}{2}$

Fractional charge: (+2/3 e or -1/3 e)

6 distinct flavours **u, d, s, c, b, t**

Quark	Symbol	Charge e	Mass MeV/c^2	Isospin (I, I_z)	Quark Flavour Quantum Number	Baryon Number $\mathcal{B}$
up	u	+2/3	1.5 - 4.5	(1/2,+1/2)	-	1/3
down	d	-1/3	5 - 8.5	(1/2,-1/2)	-	1/3
charm	c	+2/3	1000 - 1400	-	$C = +1$	1/3
strange	s	-1/3	80 - 155	-	$S = -1$	1/3
top	t	+2/3	$(174.3 \pm 5.1) \times 10^3$	-	$T = +1$	1/3
bottom	b	-1/3	4000 - 4500	-	$B = -1$	1/3

for comparison proton mass m_p = 938 MeV/c^2

Colour

Quarks come in three **colours**

"Red", "green" or "blue"

All hadrons are "colourless"

Quark Interactions

Quarks undergo strong, electromagnetic and weak interactions (also gravity)

Confinement

Quarks are confined in hadrons

Hadrons, Mesons, Baryons

Hadrons

Single free quarks have never been observed

Quarks are locked inside **hadrons**

Hadrons are bound states of quarks

e.g. (qqq) or (q anti-q)

Charge of hadron - always integer multiple of e

Two types of hadrons – **mesons** and **baryons**

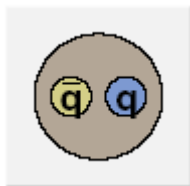
Mesons = $q\bar{q}$

Bound states of a quark anti-quark pair

Bosons - spin 0, 1, 2, …

e.g. pions $\pi^+ = (u\bar{d})$ $\pi^- = (\bar{u}d)$

$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$



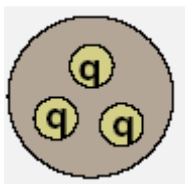
Baryons = qqq

Three quark bound states

Fermions – spin ½, 3/2, …

e.g. proton = (uud), neutron = (udd)

Anti-baryons – e.g. anti-proton = ($\bar{u}\bar{u}\bar{d}$)



Interactions

Classical Interactions

Electromagnetism and gravity

… act upon another at a distance …

… great absurdity … Newton

Interactions/Forces in Particle Physics

quarks and leptons interact via

the exchange of gauge bosons

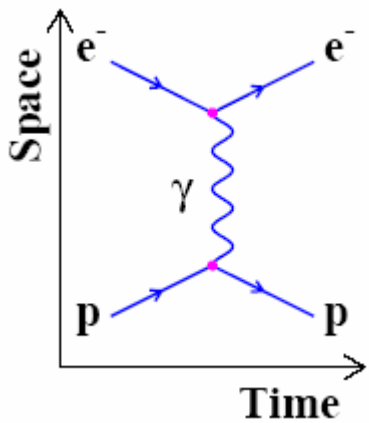
Gauge Bosons

Vector bosons – Spin 1

Mediators of strong (gluon),

electromagnetic (photon),

weak (Z^0 & $W^{\pm}$) interaction



Force	Gauge Boson	Symbol	Charge e	Mass GeV/c^2	Relative Strength
Strong	8 gluons	g	0	0	1
Electro magnetic	Photon	γ	0	0	10^{-2}
Weak	Intermediate vector bosons	Z^0 $W^{\pm}$	0 ±1	91.1876 80.425	~10^{-7}
Gravity	Graviton	g	0	0	~10^{-40}

Fundamental Forces

Strong force (gluon)

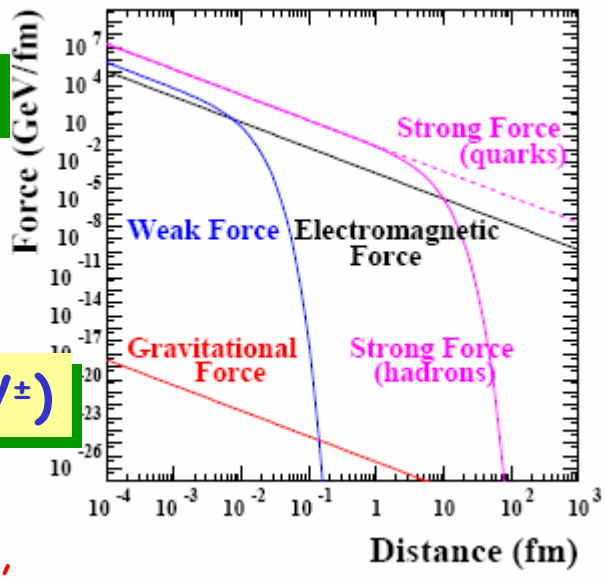
Quarks (colour charge) only

Holds hadrons (baryons and mesons) and nuclei ($^{A}_{Z}X$) together

Electromagnetic force (γ)

All charged particles

Responsible for chemistry and biology



Weak interaction (Z^0 & $W^{\pm}$)

All quarks and leptons

causes radioactive decays, fission, fusion

"Exchange of $W^{\pm}$ bosons makes the sun shine."

Gravity (graviton)

Very weak at short distance

Negligible effects in particle physics

dominant at large distance

"While gravity keeps you from flying off the earth, the electromagnetic force (mediated by the exchange of photons) keeps you from falling towards its centre."

Summary

Standard Model of Particle Physics

Describes accurately all experimental data

Many open questions, e.g. origin of mass

Matter

Three generations of fundamental particles

quarks and leptons - spin $\frac{1}{2}$ fermions

Leptons & Quarks			Charge e
ν_e	ν_μ	ν_τ	0
e-	μ-	τ-	-1
u	c	t	+2/3
d	s	b	-1/3

Quarks confined in hadrons, e.g. proton = (uud)

Antimatter: positron (e+), antiproton

Forces

Interactions between quarks and leptons

mediated by exchange of spin 1 - gauge bosons

Interaction	Gauge boson	Charge [e]
Strong	gluons g	0
Electromagnetic	photon γ	0
Weak	Z^0, $W^\pm$	0, ± 1
Gravity	graviton g	0