# PX147: Introduction to Particle Physics

*Written by Tim 'Shorts' Slater*
*Typeset by Aaron Brown*
*February 2009*

# Contents



# Disclaimer

This revision guide has been put together using the sweat, blood and tears of MathsPhys Society members. **It is intended as a revision tool and as such does not contain the entirety of the module, only the key elements. It was not complied, nor ratified by the University and most certainly not collated by any past, current or future lecturer of the afore mentioned course. As such it may be incomplete, may contain slight inconsistencies and although the utmost care has gone into ensuring they are kept minimal, slight inaccuracies**. Should you find any of the above mentioned please accept our apologies and find the time to drop us an email at the following address so we can change it in future editions, exec@warwickmathsphys.co.uk.
First edition written Tim 'Shorts' Slater and typeset by Aaron Brown in February 2009
Second edition edited by Matthew Bates and Emma Towlson in February 2010.

# 1 Introduction

Hello. This is a revision guide for Particle Physics. Please note this is not intended as a stand alone publication and there is no substitute for hard graft and thorough thought (i.e. going to the lectures and doing the work sheet problems and practising exam papers.) Having said that I hope any bits of the subject you may be unsure about are clarified and your understanding enriched by reading this. So without further ado.

# 2 Revision of A-level

This section is going to consist mainly of facts you should know and there will be relatively little discussion.
There are 3 guiding principles in particle physics:

1. Composition - Smaller particles making bigger ones
2. Symmetry - A regularity or simplicity in the constituents or their interactions
3. Unification - Understanding different phenomena under one physical law

Elementary particle - has no structure, is point-like, is as simple as it can be.
$1eV$ the energy gained by an electron when accelerated through $1V$.
$1eV = 1.602 \times 10^{-19}J$. Get used to converting between $J$ and $eV$'s and learning quantities in terms of $eV$'s as this will save you a lot of time.
Units of mass from this: $\frac{eV}{c^2}$ Units of momentum : $\frac{eV}{c}$

$$m_e \simeq 0.5\frac{MeV}{c^2} \; m_p = m_n \simeq 1\frac{GeV}{c^2}$$

**De Broglie wavelength** $\lambda = \frac{h}{p}$

## 2.1 Quarks

These are elementry particles with properties as follow. Note quarks are, in general, heavier than leptons.

| Charge (C) ↑ | ⟶ Mass $\frac{GeV}{c^2}$ | | |
|---|---|---|---|
| $+\frac{2}{3}$ | Up(u) $\sim 0.3$ | Charm(c) $\sim 1.5$ | Top(t) $\sim 175$ |
| $-\frac{1}{3}$ | Down(d) $\sim 0.3$ | Strange(s) $\sim 0.5$ | Bottom(b) $\sim 5$ (also know as beauty) |

The different columns here correspond to the different "generations" or "families"

Anti-particles - Every particle has an anti-particle partner with the same mass. Everything else (charge, spin, colour), however, is exactly opposite.

Hadrons - particles composed of quarks (feel strong force) thus they are not elementary. There are 2 types of hadrons:

- Bayrons - Composed of 3 quarks ( Anti-bayrons are composed of 3 anti-quarks)
- Mesons - Composed of a quark and an anti-quark

Colour - Each quark has a quantity called colour that is either red (r), green (g), blue (b). Anti-quarks have anti-colour $\bar{r}$,$\bar{g}$,$\bar{b}$. The fact that only quarks and gluons have colour (gluons carry colour between quarks) gives us:

- Law of Composition - All hadrons must be colourless
- Principle of Confinement - All quarks are confined inside the hadron

## 2.2 Leptons

- Colourless Fermions (see below) that are not composed of quarks
- Do not feel strong force and do not interact with gluons

**Lepton Table**

$\longrightarrow$ Mass $\frac{GeV}{c^2}$

| Charge (C) $\uparrow$ | | | |
|---|---|---|---|
| $-1$ | Electron $\sim 5 \times 10^{-4}$ | Muon $\sim 0.105$ | Tau $\sim 1.77$ |
| $0$ | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |

Where $\nu$ is a neutrino and $m_\nu < 1\frac{eV}{c^2}$

Again the above columns are called generations and each generation has an associated lepton number (+1 for all the above, −1 for their anti-particles). These numbers are conserved over short time scales (such as particle decays) but not in $\nu$-oscillations.

$$\text{Total Lepton Number} = N_e + N_\mu + N_c \ \text{ which is always conserved}$$

Spin is the intrinsic angular mometum of a particle. It is quantised in units of $\frac{\hbar}{2}$ in a particular direction.

Fermions are particles with spin $(z + \frac{1}{2})\hbar$ where $z$ is an integer.

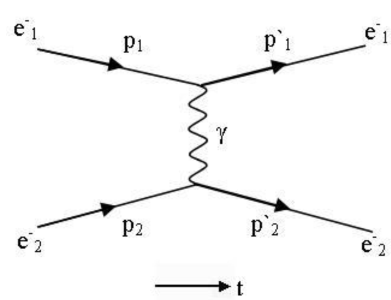
Bosons are particles with spin $z\hbar$, again $z$ is an integer.

Now this is important: All bayrons are fermions. This comes from their quark compositions since Quarks have a spin of $\frac{1}{2}$ . All mesons are Bosons. (lots of "-ions" I know, it's quite confusing, just take some time to go over it)

Flavour - flavour is term used to describe what generation or family a particle belongs to, both for leptons and quarks.

# 3 The Feynman Diagram

Right, this is best described via an example. So we will start simply with the interaction between two electrons, here's the diagram:




So what's going on here?

2 Electrons are coming from the left with energies $E_1$ (ie momentum $p_1$) and $E_2$ (ie momentum $p_2$). They interact (collide) with each other via the emission of a photon.

2 Electrons are leaving (to the right of the diagram) with energies and momenta $E_1'p_1'$ and $E_2'p_2'$ respectively. Note that the only change is the momentum - this is an example of Elastic Scattering.

So to find the momentum of the photon we note that momentum is conserved at each vertex.

$$p_\gamma = p_2' - p_2 = p_1 - p_1'$$

$$\implies p_1' + p_2' = p_1 + p_2$$

By noting that energy is conserved at each vertex we can derive a similar expression for energy. Photons like these are referred to as a virtual particles (Note: not all virtual particles are photons). Normal particles are constrained by $E = \sqrt{p^2c^2 + M_0^2c^4}$ but Virtual Particles can break this.This is allowed to happen because of the Uncertainty principle, but it is limited so that we can't physically detect it. So $\Delta E\Delta t \leq \frac{\hbar}{2}$ $\Delta p\Delta x \leq \frac{\hbar}{2}$ i.e the photon can 'borrow' a large energy for a small time or a small energy for a longer time. Furthermore we never see this photon we just infer its existence from the properties of the interaction.

# 4 The Fundamental Interactions

There are 4 fundamental interactions. They have the properties listed in the table below. Note that a gauge boson can be thought of as "the thing that carries the force"

| Interaction | Relative Strength | Range | Gauge Boson |
|---|---|---|---|
| Strong | 1 | $10^{-15}$m | gluons(g) |
| Electromagnetic | $\frac{1}{137}$ | $\infty, (\frac{1}{r^2})$ | photons ($\gamma$) |
| Weak Charged/Neutral | $10^{-9}$ | $10^{-18}$ | $W^{\pm}/Z^0$ |
| Gravitational | $10^{-38}$ | $\infty, (\frac{1}{r^2})$ | graviton, G (?) |

So what are the properties of the gauge bosons?

| Gauge Boson | Mass | Charge | Spin | Other Characteristics |
|---|---|---|---|---|
| Gluons (g) | 0 | 0 | 1 | colour and anti-colur |
| Photon ($\gamma$) | 0 | 0 | 1 | - |
| $W^{\pm}$ | $80.4\frac{GeV}{c^2}$ | $\pm1$ | 1 | weak-isospin |
| $Z^0$ | $91.2\frac{GeV}{c^2}$ | 0 | 1 | weak-isospin |
| Graviton | 0 | | 2 | - |

Let's look at things in a little more detail.

## 4.1 Strong Interaction

The strong interaction is responsible for binding quarks into hadrons and hadrons into nuclei. It is mediated in hadrons by gluons which carry colour (and anti-colour). Colour is continually being exchanged between quarks by gluons inside hadrons. Gluons never carry flavour or electric charge. So charge and flavour are always conserved in strong interactions. Note also that in a Feynman diagram, colour is always conserved at vertices and overall, since the interaction by gluons occour only inside the hadrons the total colour remains constant, i.e. (no colour, remember law of composition). The strong interaction is mediated between hadrons by pions, which have a range of $\sim 10^{-14}m$, $m_\pi \simeq 0.14\frac{GeV}{c^2}$
Quark compositons:

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

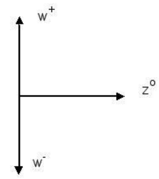
## 4.2 Electromagnetic Interaction

The electromagnetic force is one with which we are familiar so not a lot needs to be said. It is responsible for everyday contact forces. Its source is electric charge and it conserves this quantity along with colour, flavour and lepton number.

## 4.3 The Weak Interaction

The weak interaction is responsible for $\beta$-deacy, the decay of heavy quarks, the matter/anti-matter asymmetry of the universe and neutron oscillations. It has a range of $\sim 10^{-18}m$. Its fundamental strength is stronger than the electromagnetic force, but when you intergrate these over their ranges it turns out to be less.

The weak interaction is mediated by the $W^{\pm}$ and $Z^0$ bosons. Quarks and leptons interact under the exchange of these bosons. Now the charged weak interaction always changes flavour, and is the only interaction to do so. While the neutral weak interaction never changes charge or flavour. The weak "charge" is called weak-isospin, which should not be confused with spin.
$W^{\pm}, Z^0$ carry 1 unit of weak-isospin with z-component as shown in the diagram:




Quarks and leptons also carry $\frac{1}{2}$ a unit of weak-isospin.

## 4.4 Gravity

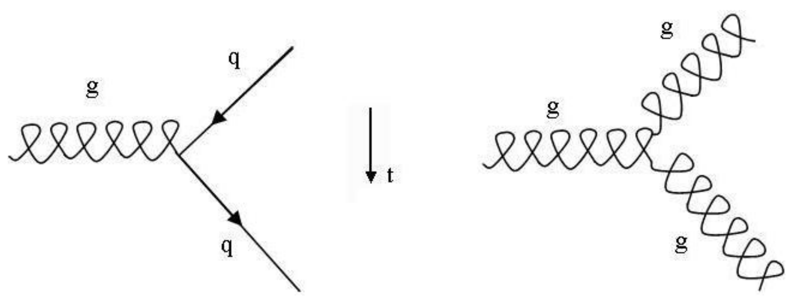
Gravity is too weak to be of any relevance in particle physics so we ignore it. The only piece of information about it relevant to this course is that it is mediated by the graviton.

# 5 Application

Using the above information we can classify particles by the interactions they undergo (or feel).

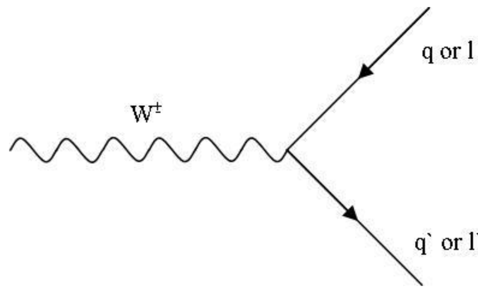
| | EM | Weak | Strong | Gravity |
|---|---|---|---|---|
| Quarks | √ | √ | √ | √ |
| Charged Leptons | √ | √ | X | √ |
| Neutrinos | X | √ | X | √ |

Strong interaction is responsible for interactions of the form (where q denotes a quark and g denotes a gluon).

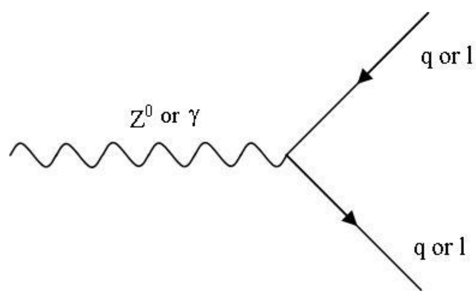



In these the incoming and outgoing quark have the same flavour, but different colour.

The weak interaction is responsible for interactions of the form:




I.e. where a particle (quark or lepton) comes in and emits a $W^{\pm}$ boson, undergoing a charge change of $\pm 1$ and an allowed flavour change (note that a quark cannot change to a lepton due to conservation of baryon and lepton numbers).
The weak and EM interactions are also responsible for interactions of the form:




ie. where a quark comes in and a quark goes out or a lepton comes in and a lepton goes out.
Note that in all the above we can always replace any chosen incoming particle by an outgoing anti-particle.

# 6 Symmetries

As I said earlier, symmetry is a regularity of a system. This helps us, as physicists to simplify its mathematical descriptions. By Noether's theorem we know that any mathematical symmetry is related to a physical conservation law, as shown in the table to follow.

Symmetries may be respected in given dynamical systems, or the laws of physics themselves. They may be exact, approximate, "badly broken" or "maximally broken". Experience and theory leads to a heirarchy about which symmetries are likely to be broken.

There are 2 main symmetry categories - Space and Time, and Internal. These are further subdivided into continuous and discrete. Below is a table for space-time symmetries and which forces follow these symmetries.

| Type | Symmetry | Meaning | Related conservation Law | Respected by which Forces |
|---|---|---|---|---|
| Continuous | Time Translation | Laws independent of "when" | Energy | All |
| | Space Translation | Laws independent of "where" | Momentum | All |
| | Rotational | Laws independent of orientaion | Angular momentum | All |
| Discrete | Parity | Change $(x, y, z) \to (-x, -y, -z)$ | Conservation of parity | Strong and Electromagnetic (not weak) |
| | Time-Reversal | $t \to -t$ | None | Strong and Electromagnetic ( Not weak) |

Internal Symmetries are symmetries after transformations of the degress of freedom of the particles themseleves. Again we will list them in a table, but I will omit the meaing of the symmetries as we are only concerned with them to identify allowed and forbidden interactions.

| Symmetry | Conservation Law | Forces Respected by |
|---|---|---|
| "Phase invariance " | Electric Charge | All |
| Colour transfer (SU(3)) | Colour | All |
| Weak isospin (SU(2)) | Weak isospin | All |
| Flavour transfer | Flavour | Strong, Electromagnetic |
| Charge Conjugation (Change of sign) | "C" Quantum number | Strong, Electromagnetic |
| "Phase" inavrience for leptons | Lepton number | All |
| "Phase" Invarience for quarks | Bayron number | All |

The interesting conservation law from the above is baryon number, this is very similar to lepton number and its conservation implies quarks can only be created or destroyed in pairs. Therefore, the total number of quarks = Total number of anti-quarks(Note: A Quark's Baryon number is $\frac{1}{3}$). However we see this is not the case and so it is thought this conservation law was violated earlier in history by some interaction which has not been discovered yet.

# 7 Hadronic Decays

Almost all hadrons decay since they are unstable and lower energy states are preferred by particles since they are more stable. However, when they decay, they can decay in different ways to different groups of particles so we define the "Branching function", which defines the probability of a particular decay by a given particle. Bearing in mind we normally have more that just 1 particle in our experiments

$$BF = \frac{\text{Number of particular decay}}{\text{Number of all possible decays}}$$

Furthermore, hadrons (and most elementary particles which also decay) decay at a constant probability per unit time $\Gamma$. $\Gamma$ is called the decay rate.
After a bit of algebraic manipulation of terms we arrive at, $P(t)\Gamma dt = -\frac{dp}{dt}dt$ which implies $P(t) = Ae^{-\Gamma t}$
It is probably worth having a look at the derivation of this in your notes.
From this we can obtain the mean lifetime of particle:

$$\tau = \int_0^\infty p(t).dt \text{ Where } t = \text{decay time}$$

$$= \frac{1}{\Gamma}$$

This is the time for which $\frac{1}{e}$ of the particles still exist. And that's all you need to know.

# 8 Relativity

I am not going to go into too much detail since this should be covered in the module PX132: Mechanics and Relativity. However, this is all you need to know for this module.

If we have a particle moving towards another particle that isn't moving[1] we can also think of it as both particles having a velocity of half the velocity of the moving particle. This is another inertial frame of reference.

So we can relate the position, time, momentum and energy of a particle in the lab frame (Z) to the position, time, momentum and energy in another inertial frame ($z'$) via the equations.

$$\begin{array}{rcl} x' & = & \gamma(x - \beta ct) \\ y' & = & y \\ z' & = & z \\ ct' & = & \gamma(ct - \beta x) \\ p'_x & = & \gamma(p_x - \frac{\beta E}{c}) \\ p'_y & = & p_y \\ p'_z & = & p_z \\ \frac{E'}{c} & = & \gamma(\frac{E}{c} - \beta p_x) \end{array} \quad \text{Where } \beta = \frac{v}{c}, \gamma = \frac{1}{\sqrt{1-(\beta)^2}} \text{ Where V is the velocity of one frame relative to the other .}$$

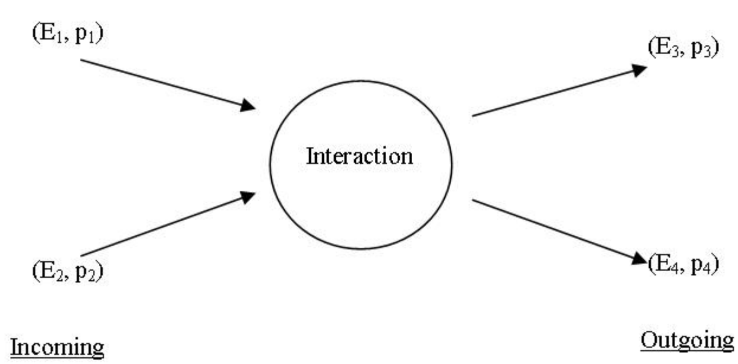
Please note, here we are assuming motion only in the $x$ direction.
Here is a diagram:


Where $\Sigma'$ is travelling with a speed $v$ relative to $\Sigma$
Also:

$$(\text{Rest energy of particle })^2 = (\text{Total energy })^2 - (\text{Momentum} \times \text{speed of light })^2$$

$$m_0^2c^4 = E^2 - p^2c^2 = E' - p'^2c^2$$

You should also be aware that total energy of a particle is the centre of momentum frame defined as $p'_2 = -p'_1$ Where we have 2 particles colliding as follows:




[1] we call this the lab frame which is a particular frame of reference

So we have $p_{total} = 0$ which implies $P_4' = -P_3'$. You should be aware of the various channels that this interaction can undertake and how these are Lorentz invariant. Their physical interpretation is the $(maximum\, mass)^2$ - the square of the maximum mass of the final state. One example of this is the s-channel.

$$S = \left[ \frac{\left(\frac{E_1}{c} + \frac{E_2}{c}\right)^2 - (\underline{P}_1 + \underline{P}_2)^2}{c^2} \right]$$

# 9 Particle Physics in the Natural World

Natural radioactivity is the primary source of geothermal energy[2]. We also get particles from cosmic rays, consisting of protons, neutrinos and some heavier nuclei. These have a wide range of energies from $1GeV$ to more than $10^{11}GeV$. The highest energies are thought to be from outside the galaxy. Cosmic rays are isotropic (Come from all directions) although they are distorted by the earth's magnetic field. These particles react at $\sim 15km$ up to produce hadronic showers.
They strongly interact with an air nucleus to produce 90% pions and a few % of kaons. These decay to muons, electrons and neutrinos.
pions $\rightarrow \mu$'s and $\nu_\mu$'s Muons $\rightarrow \nu_\mu, e^-, \bar{\nu_e}$ Kaons $\rightarrow \mu$'s and $\nu_\mu$'s

## 9.1 Neutrino Sources

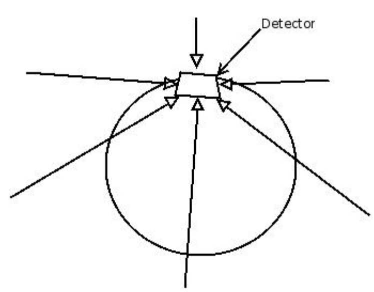
There are 3 main sources of neutrino, you should know what these are and know a little bit about them.

### 9.1.1 Atmospheric Neutrinos

Atmospheric neutrinos are generated in cosmic ray showers. We use a large water detector to identify, via light flashes, $\nu_e$ and $\nu_\mu$. Now we would expect the ratio

$$R = \frac{\text{Number of Muon reactions}}{\text{Number of electron reactions}} = 2$$

but we observe that $R \simeq 1$ for long path lengths, across the earth.



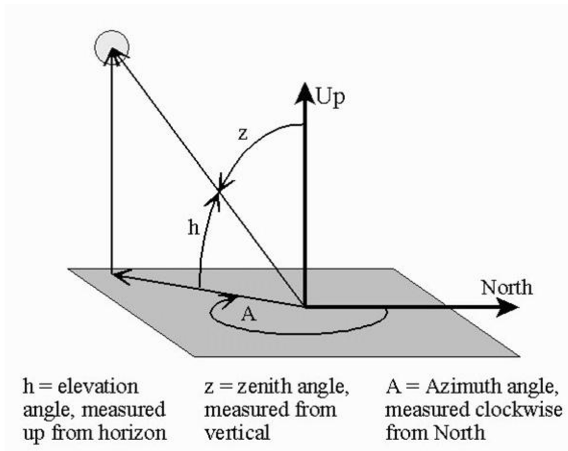

Where the arrows indicate neutrino paths, Note that the Earth is effectively transparent to neutrinos, so we have an approximately isotropic dispersion.
We can work out the path lengths of the neutrinos to be:

$$L = \frac{H}{cos\theta_z} \text{ for } cos\theta_z > 0.1 \text{ (Down)}$$

$$L = 2R_{earth}|cos\theta_z| \text{ for } cos\theta_z < -0.1 \text{ (Up)}$$

[2]The heat of the earth's interior

Where $H$ is the top of the atmosphere, $\sim 15km$, and $R_{earth}$ is the radius of the earth. Where $\theta_z$ is the zenith angle, which is the angle made between the perpendicular line to the Earth's tangent at the point we are considering.




So $\theta_z = 0$ for downward particles and $\theta_z = \pi$ for upward particles
This leads to the conclusion that $\nu_\mu$ are disappearing for path distances $> 1000km$ for particles $>$ few $100MeV$. This phenomenom is explained by neutrino oscillations where the neutrinos change flavour.

### 9.1.2 Solar Neutrinos

Main source of solar energy is nuclear fusion where

$$4P \rightarrow^4 He + 2e^+ + 2\nu_e + 26.7MeV$$

Via some "intermediate" processes which we don't need to worry about.
The sun radiates energy and neutrinos isotropically and it was recently discovered that:

$$\frac{\text{Flux of electron Neutrino on Earth's surface}}{\text{Expected flux of electron neutrinos on Earth's surface}} \simeq \frac{1}{3}$$

and

$$\frac{\text{Flux of all expected Neutrinos}}{\text{Expected flux of electron neutrinos on Earth's surface}} \simeq 1$$

This is explained again by electron neutrinos oscillating into other flavours between the Sun and the Earth.

### 9.1.3 Supernovae Neutrinos

Here protons and electrons are forced together to form a neutron and an electron neutrino in a sort of inverse beta decay, and that's all you need to know.

## 9.2 Electromagnetic Fields

This section is mostly a question of knowledge of formulae and then knowing how to apply them - and that is knowledge which only comes through practice.

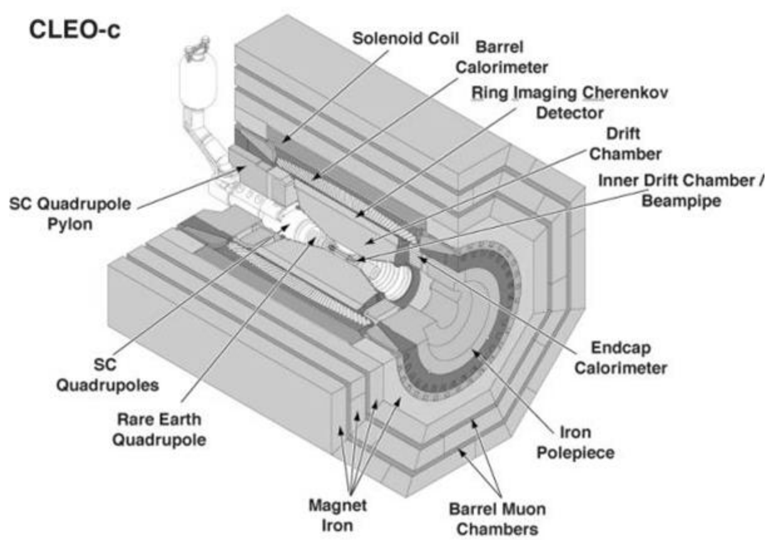
$$\text{Lorentz Force Law } \vec{F} = q(\vec{E} + \vec{V} \times \vec{B})$$

$$\text{Work Done } = \int_c \vec{F}.\vec{dl}$$

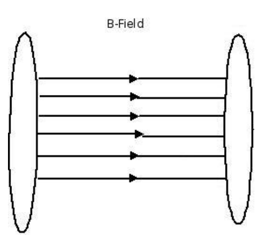
The important thing to notice is that in the absence of an electric field and with a constant magnetic field, no work is done on the particle by the magnetic field since $\vec{F}.\vec{dl} = 0$ so $|\vec{v}|$ is constant.
Using centripetal acceleration from circular motion we obtain that:

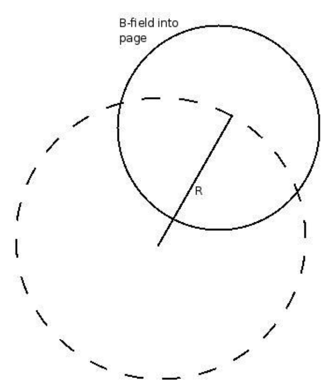
$$p = qBr$$

Where $p$ is the momentum of the particle and $r$ is the radius of the curvature.
We use magnetic fields to detect charged particles. So we can analyse particle interactions.
The conventional detector is called a drift chamber. It is filled with a particular gas and charged particles ionise the gas as they pass through. The wires have a high positive potential to attract the liberated elecrons and give a pulse. These pulses are recorded and the paths reconstructed by a computer




This allows us to calculate the radius of curvature of the electrons. Since the applied magnetic field is known, the energy and momenta of these electrons can be determined.




Helices are often executed in the chambers. These chambers are also very similar to cyclotrons where the magnetic field is varied to maintain a constant radius.

### 9.2.1 Ionisation by Charged Particles

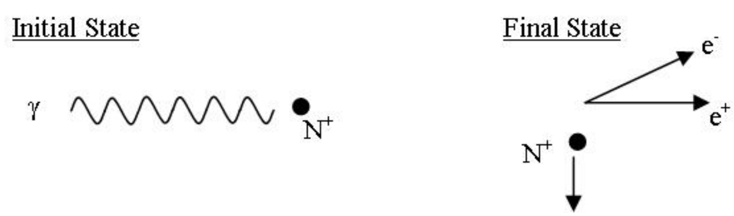
When high energy particles pass through matter they lose energy via ionisation or exciting atoms. Most of this energy is given to atomic electrons which are detected by a gas avalanche in a high E field or scintillation[3] in certain materials.

### 9.2.2 Bremsstrahlung - "Braking Radiation"

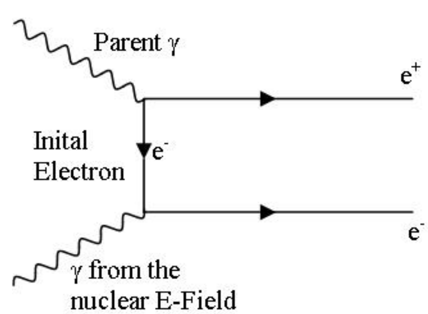
This is applicable only to charged particles. When an energetic charged particle moves through matter it loses energy due to interactions with the matter it is passing through. It undergoes an acceleration at each interaction and a change of direction or a loss of energy. Each of thse interactions has a possibility of emitting a photon, which has a significant fraction of the charged particle's mass (Note that the number of interactions is an inverse function of the projectile's mass). A photon is emitted once every radiation length $X_0$, which is a property of the material only.

### 9.2.3 Pair production by Photons

This phenomena occurs when a high energy photon passes through matter. It can produce an $e^+e^-$ pair in the electric field of the nucleus (or an electron but this is less likely). In general a photon will have such an interaction after a specific distance, $X_0$, known as the radiation length.




The Feynman Diagram for this




### 9.2.4 Hadronic Interaction length

When hadrons are fired through a thick material, they have a fixed probability per unit distance to interact with a nucleus; similar to what we saw for charge particles. This fixed distance per interaction, $\lambda_I$, is called the hadronic interaction length. It is independent of the energy and the type of projectile for a given material and is typically $10 - 30$ times larger than the radiation length.

[3]Scintillation is another word for glowing, the energy gets given to these material and they emit photons at a rate proportional to the energy they get

#### 9.2.5 Probability of Interaction

In "thick" material ( $t >> \frac{1}{R}$) The probability that a particle interacts in a given pathlength $dx$ is given by a constant $R$ ie.

$$-\frac{dP}{dx}dx = P(x)Rdx \implies P(x) = e^{-Rx}$$

So we get a mean depth of interaction:

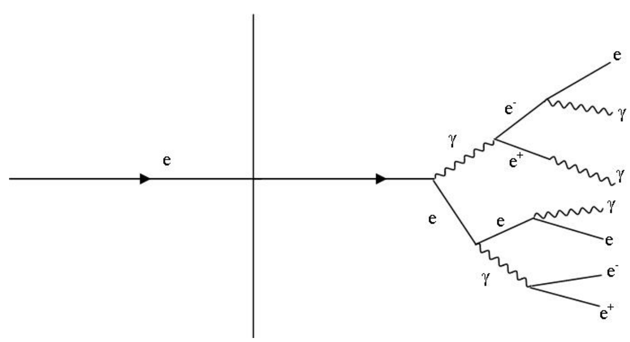
$$\bar{X} = \int_0^\infty x \left|\frac{dP}{dx}\right| dx = \int_0^\infty Rxe^{-Rx}dx$$

So we get $P(x) = e^{-\frac{x}{\bar{x}}}$, where $\bar{x}$ is the radiation length ($X_0$) or the hadronic interaction length ($\lambda_I$ ) depending on what type of particle (lepton or hadron) we are talking about.

# 10 Calorimeters

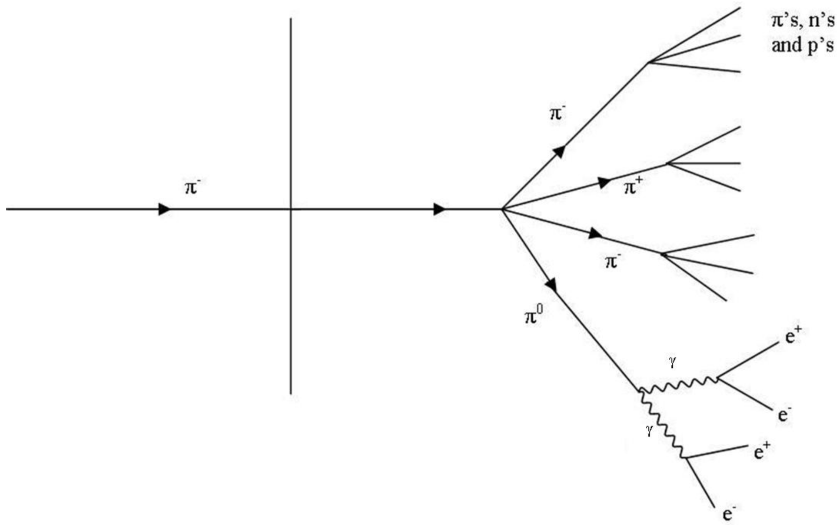
## Electromagnetic

When a high energy photon or electron enters a thick material it interacts once every $X_0$ and makes a photon. This photon makes a $e^+e^-$ pair after another $X_0$, and this process continues creating an electromagnetic shower. The electrons lose energy through ionisation, and if the material is thick enough and instrumented with ionisation measuring devices, we can measure the energy of the incoming particle as all particles are contained.




## Hadronic

A similar shower can develop from hadronic interactions. Some $\pi^0$'s are usually formed and decay into two photons creating electromagnetic showers. Particles again deposit energy and we can measure the energy of the incoming particle if the entire shower is contained




Note due to statistical fluctuations in the electromagnetic component and degree of containment, hadronic calorimeters not as good as electromagnetic calorimeters. Furthermore as $\lambda_I >> X_0$, hadronic calorimeters are bigger than electromagnetic calorimeters.

# 11 The Questions

Normally the lecture course finishes with the big, remaining questions of particle physics. Unfortunately these are too big for this revision guide. But you should be aware of them.

# 12 Conclusion

Well that's that. I reiterate that now you should really attempt some exam papers to apply the knowledge that you hopefully have gleamed. Another useful exercise is to draw out all the Feynman diagrams you can and make sure you know what interaction is responsible for each. Learn the formulae and definitions and make sure you understand the main concepts involved. I leave you with the words of Jules Renard

**"Failure is not the only punishment for laziness; there is also the success of others."**

Good Luck!