Lecturer: Dr F. Loebinger

## Books:

- Martin, B.R. \& Shaw, G - Particle Physics (Wiley) (recommended)
- Perkins, D.H. - Introduction to High Energy Physics (CUP) (advanced)


## Introduction

1897 - Electron discovered by JJ Thomson (born in Cheetham Hill, student here.)
1919 - Proton discovered by Rutherford (Manchester)
1932 - Neutron discovered by Chadwick (Cambridge)
Lifetimes:
Proton $>10^{32}$ years (decay never seen)
Electron $>10^{23}$ years
Neutron $\sim 900$ seconds
1928 - Dirac;
$E^{2}=p^{2} c^{2}+m_{0}{ }^{2} c^{4}$
In theory;
E in GeV
Momentum $\mathrm{GeV} / \mathrm{c}$
Mass $\mathrm{GeV} / \mathrm{c}^{2}$
In practice:
$\mathrm{E}, \mathrm{P}$ and M in units of GeV , where $c=1$ and often $\hbar=1$.

$$
E^{2}=p^{2}+m_{o}^{2}
$$

$m$ normally means the rest mass of the particle $m_{0}$.
Therefore:

$$
\begin{aligned}
& E= \pm \sqrt{p^{2}+m^{2}} \\
& m\left(\equiv m_{0}\right) \text { for } e^{-}=0.5 \mathrm{MeV} / \mathrm{c}^{2}
\end{aligned}
$$

What is the negative energy?

$\mathrm{a}=$ Positive E electron moving with positive KE
b $=$ Forbidden region
$c=$ Negative E electron moving with negative KE

Dirac's "hole" interpretation - ridiculed by Pauli.
Based on band theory of semiconductors.
Consider electrons rest mass $=m c^{2}$
"Vacuum" has all negative energy states full. Electron is a fermion $\rightarrow$ cannot have electrons going down into the negative energy state because of Pauli exclusion. If you add positive energy to the negative energy states, you can promote the state to positive energy. A hole is created in the negative energy system created by absorbing $E>2 m c^{2}$. (Not all the positive states are full).

This leads to a hole (a negative energy particle) plus an extra positive energy electron.

$e^{-}$is the positive E state, while $e^{+}$is the negative.
Feynman diagram.
Another interpretation:


Pair production
A hole can be filled by an electron dropping down with the emission of energy.


Feynman's explanation (Fred's simplified version):
Take a positive energy $e^{-}$. Wave function: $\Psi(x, t)=\mathrm{e}^{\frac{i}{\hbar}\left(p x-E^{\dagger} t\right)}=\mathrm{e}^{k x-\omega^{+} t}$
Negative energy $e^{+}$. Wave function: $\Psi(x, t)=e^{\frac{i}{\hbar}\left(p x-E^{+} t\right)}=e^{\frac{i}{\hbar}\left(p x-\mid E^{-}(-t)\right)}$
$=$ particle of positive energy (i.e. $\left|E^{-}\right|$is + ve) moving backwards in time $(-t)$.
A normal positive energy particle in a magnetic field will experience a force which is proportional to $(-e) \underline{v} \times \underline{B}$.

For this positive energy electron moving backwards in time, this force is now proportional to $(-e) \frac{d \underline{x}}{d(-t)} \times \underline{B}$, i.e. the force is proportional to $(+e) \frac{d \underline{x}}{d t} \times \underline{B}$. This is equivalent to a particle of the opposite charge moving forwards in time.

Therefore we have the negative energy particle being equivalent to the positive energy particle moving backwards in time, which is equivalent to a positive energy particle of opposite charge moving forwards in time.

Therefore for every particle with positive energy, there exists a negative energy state which is equivalent to a positive energy particle with opposite electric charge.

This is true for all additive quantum numbers, of which the electric charge is just one. These are the antiparticles.

## 1955 - Chamberlain et al.

Beam of protons accelerated in BEVATRON.
$p_{\text {beam }}+p_{\text {target }} \rightarrow \bar{p}+p+p+p$
Detected as the antiproton would combine with a proton and annihilate - energy from that detected.
How much kinetic energy would have been needed in the proton beam to let this reaction happen?

Relativistic kinematics:
$\beta=\frac{v}{c} \equiv v(c=1)$
$\gamma=\frac{1}{\sqrt{1-\beta^{2}}}$
$E=\gamma m_{0} c^{2} \equiv \gamma m$
$p=\gamma m_{0} \nu \equiv \gamma m \beta$
$E_{k}=E-m_{o} c^{2}$
$E^{2}-p^{2} c^{2}=m_{0}{ }^{2} c^{4}$ the invariant mass sequared.
$E^{2}-p^{2}=m^{2}$ for a single particle.
For a system of particles, $\left(\sum E_{i}\right)^{2}-\left(\sum p_{i}\right)^{2}=M^{2}$.
At threshold, particles are produced with zero momentum in the centre of mass.

## Neutron Beta Decay

An isolated neutron, i.e. one that is not part of an atom, will decay in 900 seconds (average).
Observed: $n \rightarrow p+e^{-}$.
Problems:

- Missing Energy $E_{n}>E_{p}+E_{e}$
- Missing angular momentum - all three particles have $1 / 2$
- Wrong energy spectrum of the electron

Assume $n \rightarrow p+e^{-}$. If n is at rest, then the proton and the electron must be emitted with equal and opposite angular momentum.
A 2 body decay must always give a unique value for energy of $e^{-}$. Instead, a variety of energies was observed:


However, the charge is correct.
The solution was postulated in 1934 by Fermi. He postulated the existence of the neutrino, a particle with zero (or very little) mass, zero electric charge, $1 / 2$ integral spin.
So:

$$
n \rightarrow p+e^{-}+\bar{v}_{e}
$$

The neutrino interacts only by the weak interaction, and even then weakly. Hence why is was never observed in the original experiments. It has a very low crosssection.
Take the Earth. Let $10^{10}$ neutrinos enter the north pole. Only one would react before they came out of the south pole.

Pauli says that these will never be detected, as the cross-section is so low. He bet a crate of champagne on this...

In 1959, Reines \& Cowan went to a nuclear reactor and put the neutrons into a proton target. They observed

$$
\bar{v}_{e}+p \rightarrow n+e^{+}
$$

They detected this through the $e^{+}$reacting with an $e^{-}$to form photons.
Pauli delivered his crate of champagne.
In 1935, Yukawa proposed the strongly interacting nuclear force. From the uncertainty principle, and knowing that the range of this force is around $10^{-15} \mathrm{~m}$, he deducted that the mass of the particle responsible for / mediating the strong interaction is around 150 MeV .
1937, the Muon $\left(\mu^{ \pm}\right)$was discovered. Mass around 100 MeV . This was immediately linked to the strong force - but they were wrong. It had the right mass, but all the wrong interaction properties. It was seen coming from cosmic rays at the top of the atmosphere, at ground level. It did not have strong interactions itself, therefore it was not the mediator of the strong interaction force.
It was originally called the Mu-Meson. After around 10 years, it was renamed to the Muon.

In 1947, the Pion $\left(\pi^{ \pm, 0}\right)$ was discovered. It has the right mass - 140 MeV - and has the right interaction properties. It interacted by the strong interaction. Called the Pi Meson.

Cosmic rays coming into the atmosphere. Reactions predominantly produce $\pi$ 's. This then decays into $\mu$, which can hence reach ground level. This can also decay into an electron before getting to the ground.

So, to observe the decay of a pion you have to go high up - top of the Alps. The first lifetime measurements of the Pion - photographic plates in a cocoa tin at the top of the Alps. $\pi^{ \pm} \rightarrow \mu^{ \pm}$- nothing else was seen. Here, the momentum of the muon in the rest fram was always the same - indicative of a two-body decay.

Energy conservation gave the missing mass in the reaction to be around 0 . It could either be a neutrino or a photon - but as photons are easy to detect, it couldn't be that. So:

$$
\pi^{ \pm} \rightarrow \mu^{ \pm}+v_{m}
$$

Lifetime of a pion is around $10^{-8} \mathrm{~s}$.
The neutral pion decays to two photons. This is easy to detect / measure. (1950). Mass also around 140 MeV , however the lifetime is now around $10^{-16}$ seconds.

$$
\mu^{ \pm} \rightarrow e^{+}+\ldots
$$

In the rest frame of the $\mu$, the electron does not have a unique momentum. Therefore not a two-body decay. Missing mass of around zero. Must be a neutrino. Simplest explaination is:
$\mu^{ \pm} \rightarrow e+v+\bar{v}$

## Size

If a particle has size, then it must have structure - hence it must have something inside it.
Particles with size of around 1 fm are called Hadrons.
Particles with "size" 0 can either have an immeasurably small size (i.e. very highenergy detectors needed) (now down to $<10^{-19} \mathrm{~m}$ ), or the particles have no size and are pointlike (favoured by theories) - so no structure. These particles are called leptons.
For completeness: the photon is not a lepton.
Focus on Hadrons.
Very basic Quark Model:
Quarks are constituents of the hadrons.
Obvious known properties:

- protons and neutrons have spin $1 / 2$ : fermions - Baryons $\sim 200$.
- $\quad \pi^{ \pm 0}$ have spin 0 : bosons - Mesons $\sim 100$.
- Hadrons have either integral ( $\mathrm{p}, \pi^{ \pm}$) or zero (n) electric charge.

Model was introduced is 1963 by Gell-Mann who introduced the concept of Quarks. Zweig introduced "Aces". The name "Quark" stuck.

Fred's reasoning behind the Quarks:

1) Baryons (protons, neutrons, etc.) are fermions with $1 / 2$ integral spin. $\rightarrow$ quarks must have $1 / 2$ integral spin (fermions). (Could invent a quark model with $1 / 4$ or $1 / 8$ integral spin, but this is much more complicated.)
2) Baryons must be made of an odd number of quarks.

1 quark per particle (nonsense - no better off)
3 per particle (will try)
$5,7,9, \ldots$ - but this is more complicated.
3) Mesons are bosons - integral spin. Therefore must be made of an even number of quarks.
2 (try this)
$4,6, \ldots$ - more complicated.
4) Baryons have integral or zero electric charge $Q$. Therefore quarks must have electric charge in units of thirds of an electronic electric charge $e$.
5) Mesons also have integral or zero electric charge. Pairs of quarks with thirds of $e$ must add to give 0 or $\pm 1$.

Simplest quark possibilities:
Spin $=1 / 2$
Electric charge $e / 3$
Baryons $3 q$
Mesons $2 q$
There is potential evidence for a Baryon with 5 quarks. The debate continues with this.

| Quark | Up u | Down d | Strange s | $\bar{u}$ | $\bar{d}$ | $\bar{s}$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Spin | $1 / 2$ | $1 / 2$ | $1 / 2$ | $1 / 2$ | $1 / 2$ | $1 / 2$ |
| Electric <br> charge <br> (additive <br> quantity) | $+2 / 3$ | $-1 / 3$ | $-1 / 3$ | $-2 / 3$ | $+1 / 3$ | $+1 / 3$ |
| Baron <br> number <br> (also <br> additive) | $+1 / 3$ | $+1 / 3$ | $+1 / 3$ | $-1 / 3$ | $-1 / 3$ | $-1 / 3$ |


|  | Hadrons |  |
| :--- | :--- | :--- |
| Baryons (Fermions) |  | Mesons (Bosons) |
| $q q q$ | $q \bar{q}$ |  |
| Proton $=(u u d)$ | $\pi^{+}=(u \bar{d})$ |  |


| Neutron $=(u d d)$ | $\pi^{-}=(\bar{u} d)$ |
| :--- | :--- |
| $\pi^{0}=(u \bar{u}+d \bar{d})$ (quantum mechanical |  |
| superposition) |  |
| $\bar{p}=(\bar{u} \bar{u} \bar{d})$ |  |
| $\bar{n}=(\bar{u} \overline{d d})$ | $\overline{\pi^{+}}=(\bar{u} d)=\pi^{-}$ |
| $\overline{\pi^{0}}=(\bar{u} u+\bar{d} d)=\pi^{0}$ |  |

Note that the strange quark has not yet been needed.
The time that the $\pi^{0}$ takes to decay is the time it takes to "realize" that it is its' own antiparticle, and annihilate itself.

Note that it is not possible for $p \rightarrow \pi^{+}$i.e. $u u d \rightarrow u \bar{d}$. A baryon cannot decay to just a meson.
A baryon has quantum number $(B)$ which must be conserved.
$B=1$ for Baryon
$B=-1$ for antiparticle
$B=0$ for everything else.
$\rightarrow B=1 / 3$ for all quarks
$\rightarrow B=-1 / 3$ for all antiquarks.

