Quanta to Quarks - The Standard Model

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The Quanta to Quarks option consists of a number of parts, some of which concern the "standard model" of subatomic and sub nuclear physics. It is an intricate, complex and often subtle thing and a complete study of it is beyond the scope of high school study and indeed beyond undergraduate university study. However it is important and is capable of explaining nearly all aspects of physics at its most fundamental level. Thus it is important to introduce high school students to it. The questions that then arise are:-

How much should we teach?
What is the minimum that is worthwhile teaching?
How do we teach it?

We will make a statement of what it is, in general terms, and then start looking at the details and how it applies to the everyday world.

But first let us put it in a perspective:-

1. **Inward Bound:-**

<table>
<thead>
<tr>
<th>object and size</th>
<th>$E_\gamma$, Energy of Photon with $\lambda \sim$ size</th>
<th>Energy to &quot;break up&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>grain, 1 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>virus, 100 nm</td>
<td>12 eV</td>
<td>1 meV</td>
</tr>
<tr>
<td>atom, 100 pm</td>
<td>12 keV</td>
<td>10 eV</td>
</tr>
<tr>
<td>nucleus, 10 fm</td>
<td>120 MeV</td>
<td>8 MeV</td>
</tr>
<tr>
<td>nucleon, 1 fm</td>
<td>1.2 GeV</td>
<td></td>
</tr>
<tr>
<td>quark, &lt;1 am</td>
<td>&gt; 0.12 TeV</td>
<td></td>
</tr>
</tbody>
</table>

Note 1:
The nature of the atom was established (1911) by Rutherford scattering, in which alpha particles (low mass) were scattered off a gold nucleus (high mass). There was more large angle scattering than expected from an object in which the charge was spread out over the whole atom, consistent with scattering from a small object carrying the whole charge. Only a small nucleus will have the strong electric fields necessary to deflect the alpha particle.

**Classroom activity**
Get the students to calculate how energetic an alpha particle must be in order to reach the surface of a gold nucleus in a head on collision. This is not relativistic so classical mechanics may be used. ($r_{nucleus} = 1.23 \text{ fm} \ A^{1/3}$, ans:- $E_{alpha} \sim 31 \text{ MeV}$)

In the 1960's a similar experiment (by an MIT/SLAC collaboration) in which high energy electrons were scattered off protons also produced more large deflections then were expected for the case where the proton's charge was distributed over the volume
of the proton. The results were consistent with the charge being concentrated in small volumes (such as point like quarks).

These are examples of the use of a projectile probe to study the structure of the target. The same technique is used today; high energy projectiles (produced by accelerators) are directed at targets. High energies are required for two reasons. The first is to have projectiles with very short de Broglie wavelengths; the projectile’s interaction with the target is averaged over a region of about this distance and so target structure finer than this will not be resolved, cf. radio waves. For relativistic projectiles, say with energy $> 10 \text{ mc}^2$, the wavelength is about the same as for a photon of the same energy, i.e. their mass may be neglected. The second reason is to have enough energy to produce new particles.

Note 2:-
The nucleus is made of roughly equal number of protons and neutrons. In everyday nuclear reactions, such as fission, fusion, alpha, beta and gamma decays the total number of nucleons remains the same. In all except the beta decay this conservation law is also true for protons and neutrons separately. In beta decay a proton or a neutron changes to the other kind of nucleon.

Note 3:-
The most stable, equilibrium, states of a nucleus follow a line in the n/p diagram, which becomes more neutron rich for heavier, higher Z nuclei. In order to get closer to this line of stability nuclei will discard nucleons, either individually or as a group (e.g. alpha decay) or change protons to neutrons or vice versa (beta decay). The nucleons inside a nucleus can be in higher energy states, like electrons in an atom, and can radiate this energy in the form of high energy photons (gamma decay). Which of these processes takes place depends on selection rules determined by any change having to obey various conservation laws, of energy, momentum, angular momentum. If a number of different changes are possible then the most probable one will dominate, but the other changes will take place occasionally.

2. The Standard Model:-

According to the standard model the quarks and the leptons are the fundamental building blocks of our universe. The everyday world of atoms and molecules is made up of only the first generation quarks and leptons; first generation antiparticles and higher generations only make fleeting appearances, with a couple of exceptions; the positron and the electron anti neutrino. Positrons are produced quite frequently in beta decays and neutrino interactions are so rare that once created in say beta decay they continue roaming the universe for a long time.

The standard model describes the building blocks of the universe in terms of a set of different kinds of particles and the interactions between them:-
2.1 The particles:- there are twenty four particles (all fermions):

12 leptons/anti-leptons, in 3 generations

a) leptons

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge</th>
<th>mass $\text{MeV}/c^2$</th>
<th>mass $\text{m}/\text{m}_{\text{proton}}$</th>
<th>lepton number $l_e$ $l_\mu$ $l_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>$e^-$</td>
<td>-e</td>
<td>0.511</td>
<td>0.0055</td>
<td>1 0 0</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>$\nu_e$</td>
<td>0</td>
<td>$\sim$ 0</td>
<td></td>
<td>1 0 0</td>
</tr>
<tr>
<td>mu-minus</td>
<td>$\mu$</td>
<td>-e</td>
<td>105.66</td>
<td>0.1126</td>
<td>0 1 0</td>
</tr>
<tr>
<td>mu-neutrino</td>
<td>$\nu_\mu$</td>
<td>0</td>
<td>0</td>
<td></td>
<td>0 1 0</td>
</tr>
<tr>
<td>tau-minus</td>
<td>$\tau^-$</td>
<td>-e</td>
<td>1777</td>
<td>1.894</td>
<td>0 0 1</td>
</tr>
<tr>
<td>tau-neutrino</td>
<td>$\nu_\tau$</td>
<td>0</td>
<td>$\sim$ 0</td>
<td></td>
<td>0 0 1</td>
</tr>
</tbody>
</table>

b) the corresponding anti-leptons

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge</th>
<th>mass $\text{MeV}/c^2$</th>
<th>mass $\text{m}/\text{m}_{\text{proton}}$</th>
<th>lepton number $l_e$ $l_\mu$ $l_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-plus positron</td>
<td>$e^+$</td>
<td>+e</td>
<td>0.511</td>
<td>0.0055</td>
<td>-1 0 0</td>
</tr>
<tr>
<td>electron antineutrino</td>
<td>$\bar{\nu}_e$</td>
<td>0</td>
<td>$\sim$ 0</td>
<td></td>
<td>-1 0 0</td>
</tr>
<tr>
<td>mu-plus mu-bar</td>
<td>$\mu^+$</td>
<td>+e</td>
<td>105.66</td>
<td>0.1126</td>
<td>0 -1 0</td>
</tr>
<tr>
<td>muon antineutrino</td>
<td>$\bar{\nu}_\mu$</td>
<td>0</td>
<td>$\sim$ 0</td>
<td></td>
<td>0 -1 0</td>
</tr>
<tr>
<td>tau-plus tau-bar</td>
<td>$\tau^+$</td>
<td>+e</td>
<td>1777</td>
<td>1.894</td>
<td>0 0 -1</td>
</tr>
<tr>
<td>tau antineutrino</td>
<td>$\bar{\nu}_\tau$</td>
<td>0</td>
<td>$\sim$ 0</td>
<td></td>
<td>0 0 -1</td>
</tr>
</tbody>
</table>

Note 1:-
The second and third generations charged leptons (mus and taus) are unstable and decay to lower generations. The electron hasn't anything to decay to and is therefore stable.

Note 2:-
The neutral leptons are entered as massless. However, evidence gathered over recent years of neutrino oscillations (neutrinos in flight changing generations or "flavours") requires that in at least one of the generations of neutrinos must have mass. Nevertheless these masses are likely to be still very small.
12 quarks/anti-quarks: 6 *flavours* also organised in 3 *generations*

a) quarks

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge $e$</th>
<th>mass $\text{MeV}/c^2$</th>
<th>mass $m_{\text{proton}}$</th>
<th>quark flavour numbers</th>
<th>$q_d$</th>
<th>$q_u$</th>
<th>$q_s$</th>
<th>$q_c$</th>
<th>$q_b$</th>
<th>$q_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>down</td>
<td>d</td>
<td>-1/3</td>
<td>3</td>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>up</td>
<td>u</td>
<td>+2/3</td>
<td>6</td>
<td></td>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>strange</td>
<td>s</td>
<td>-1/3</td>
<td>100</td>
<td>0.1</td>
<td></td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>charm</td>
<td>c</td>
<td>+2/3</td>
<td>1250</td>
<td>1.3</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>bottom</td>
<td>b</td>
<td>-1/3</td>
<td>4500</td>
<td>4.8</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>top</td>
<td>t</td>
<td>+2/3</td>
<td>175000</td>
<td>187</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

b) the corresponding anti quarks

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge $e$</th>
<th>mass $\text{MeV}/c^2$</th>
<th>mass $m_{\text{proton}}$</th>
<th>quark flavour numbers</th>
<th>$q_d$</th>
<th>$q_u$</th>
<th>$q_s$</th>
<th>$q_c$</th>
<th>$q_b$</th>
<th>$q_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti-down</td>
<td>$\bar{d}$</td>
<td>+1/3</td>
<td>3</td>
<td></td>
<td></td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>up</td>
<td>$\bar{u}$</td>
<td>-2/3</td>
<td>6</td>
<td></td>
<td></td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>strange</td>
<td>$\bar{s}$</td>
<td>+1/3</td>
<td>100</td>
<td>0.1</td>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>charm</td>
<td>$\bar{c}$</td>
<td>-2/3</td>
<td>1250</td>
<td>1.3</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>bottom</td>
<td>$\bar{b}$</td>
<td>+1/3</td>
<td>4500</td>
<td>4.8</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>top</td>
<td>$\bar{t}$</td>
<td>-2/3</td>
<td>175000</td>
<td>187</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

Note:
The light quark masses are not well defined. They are strongly bound to each other; bare quarks cannot be experimentally isolated for measurement. Paradoxically when they are close (within the family home) they can move quite freely, yet trying to remove them from this environment requires so much energy that another quark/anti-quark pair is created. This always present strong binding makes it difficult to determine quark masses. ($m_{\text{proton}} = 938.3 \text{ MeV}/c^2 = 1.673 \times 10^{-27} \text{ kg} = 1.0073 \text{ u}$)

2.2 The interactions: there are four kinds of forces.

<table>
<thead>
<tr>
<th>force</th>
<th>exchange boson</th>
<th>&quot;charge&quot;</th>
<th>range</th>
<th>mass $\text{Gev}/c^2$</th>
<th>mass $m_{\text{proton}}$</th>
<th>how many different kinds?</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravity</td>
<td>graviton</td>
<td>mass</td>
<td>infinite</td>
<td>zero</td>
<td></td>
<td>one</td>
</tr>
<tr>
<td>electromagnetic</td>
<td>photon</td>
<td>electric</td>
<td>infinite</td>
<td>zero</td>
<td></td>
<td>one</td>
</tr>
<tr>
<td>weak</td>
<td>$W^+$</td>
<td>weak</td>
<td>1 am</td>
<td>80.43</td>
<td>85.72</td>
<td>three</td>
</tr>
<tr>
<td></td>
<td>$W^-$</td>
<td></td>
<td></td>
<td>80.43</td>
<td>85.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z^0$</td>
<td></td>
<td></td>
<td>91.19</td>
<td>97.2</td>
<td></td>
</tr>
<tr>
<td>Fundamental strong</td>
<td>gluon</td>
<td>colour</td>
<td>infinite</td>
<td>zero</td>
<td></td>
<td>eight</td>
</tr>
</tbody>
</table>

Which particles "feel" which forces:-
<table>
<thead>
<tr>
<th></th>
<th>gravity</th>
<th>weak</th>
<th>electromagnetic</th>
<th>strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>charged leptons</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>neutral leptons</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>quarks</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>photons</td>
<td>y</td>
<td>n</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>n</td>
</tr>
<tr>
<td>$W^+$, $W^-$</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>gluons</td>
<td>y</td>
<td>n</td>
<td>n</td>
<td>y</td>
</tr>
</tbody>
</table>

**Note 1:**

The interactions are mediated by exchange bosons, meaning that particles interact and exert forces on one another by exchanging a particle. Each force has a different kind of particle. This model originally arose from the electric force, where a charge (on a particle) produces a surrounding field and another charge (on a particle) feels a force. When the electromagnetic radiation was found to consist of photons the idea of interaction by particle exchange was born.

**Note 2:**

When the nucleus was found to contain protons and neutrons, the question arose; what keeps the protons together? A strong "nuclear" force was proposed. Yukawa applied the concept of force using exchange particles. To explain the short range a massive particle was needed. Its mass was predicted to be about 1/7 of the mass of the proton. Shortly thereafter a particle with about the right mass was found, but its range in matter was too large. This turned out to be the muon. The nuclear exchange particle, the pion, was found soon after. We now regard the relationship of inter-nucleon force to the weak and strong forces to be like that of inter-atomic force to the electromagnetic force holding an atom together. This is reminiscent of the intermolecular Van der Waals force, which is the result of the adding the electromagnetic forces, from the component electrons and nuclei, outside the neutral molecule.

**Note 3:**

The quarks are held together in two kind of groups
(a) **baryons:** three quarks or three anti-quarks and
(b) **mesons:** a quark/anti-quark pair

The these two groups are collectively known as **hadrons** (particles which can feel the strong force). These quarks determine the properties of the particle, however in addition to these so called valence quarks there is a surrounding cloud of quark anti-quark pairs of all flavours called "sea" quarks, all bound by gluons.
Note 4:-
The stuff of everyday matter (atoms) is made up of electrons and the lowest mass baryons viz the nucleons:-

proton       = 2 up-quarks + 1 down-quark = uud  
neutron      = 1 up-quark + 2 down-quarks = udd

The order doesn't matter, uud = udu = duu.

Why no uuu or ddd? They do exist, but only in higher mass baryons, which will decay to the lower mass (energy) state by for example creating a charged pi meson

\[ \Delta^{++} (\text{uuu}) \Rightarrow p(\text{uud}) + \pi^+ (\bar{d},u) \]

Note 4:-
The properties of the interaction are described by a theory called quantum chromodynamics. The equivalent of electric charge (in electrodynamics) for the strong interaction is called "colour".

Whereas in electrodynamics there are two charges, + and -, there are three colour charges; red (R), green (G) and blue (B). These are needed in order to explain baryons containing three otherwise identical quarks. Baryons contain one of each colour. Originally red, blue and white were chosen, but then it was realised that the three colour systems used in colour printing, photography and TV were more appropriate. The three colours when added together produce white or "colourless". Hadrons have to be colourless. The term colour is used in this context purely by way of analogy; of course the colour charges of quarks bear no relation to colours as experienced in everyday life.

Antiquarks posses anticolour:-

antired (\(\bar{R}\))  = white - red  = cyan  
antigreen (\(\bar{G}\))  = white - green  = magenta  
antiblue (\(\bar{B}\))  = white - blue  = yellow

Quarks cannot possess anticolour and antiquarks cannot possess colour. Antibaryons, containing three antiquarks are also colourless.

Mesons, containing a quark/antiquark pair, must also be colourless and so the pair must possess opposite colours; eg a cyan antiquark(\(\bar{R}\)) together with a red quark.

Gluons, the messenger bosons for the strong force, carry a colour and an anticolour and so can change the colour of quarks within a hadron, which must however remain colourless.

Like colours repel and unlike colours attract, however because the quarks inside a hadron can change colours the situation is more complex and the colour states are not pure colours but are mixes of the three colours in different ways.
2.3 **Particle classification:-**

2.3.1 **Generations.**

first generation: leptons \( \left( \nu_e, e^- \right) \) quarks \( \left( u, d \right) \)

second generation: leptons \( \left( \nu_\mu, \mu^- \right) \) quarks \( \left( c, s \right) \)

third generation: leptons \( \left( \nu_\tau, \tau^- \right) \) quarks \( \left( t, b \right) \)

The six different varieties of quarks are often called the quark **flavours**. The flavour names arose historically. The first quark model (1964) needed only three quarks: up, down and strange. The up and down were introduced since only two kinds of quark were needed to explain ordinary matter and, like proton and neutron, the two were considered to, somehow, be two different states of the same thing. And the mathematics of such systems was similar to that of spin: spin-up, spin-down. The name strange was introduced since the addition of the strange quark was needed to explain the observed behaviour of some particles produced in collision of high energy cosmic ray particles with matter. The particles were produced quickly and in pairs (in the strong nuclear reaction, but decayed slowly (ie traveled farther) and decayed separately. The quark model explanation was that one of the pair of particles contained a strange quark and the other an anti-strange quark and that the decays involved the flavour changing weak interaction, a much slower process.

2.3.2 **Leptons, mesons, baryons**

Originally the terms described the mass of particles, leptons (light), baryons (heavy) and mesons (in between). Their behaviour, modes of interactions etc, seemed to also depend on the mass. Over the years, new particles with similar behaviour but much larger masses were discovered in each of the groups. The terms now describe the quark content of particles; leptons are quarkless fermions, mesons are a bound state consisting of a quark/antiquark pair and baryons have three quarks.

2.3.3 **Particles and antiparticles**

A particle and its antiparticle have exactly the same mass but have opposite values for quantum numbers (originally this was electric charge only but later it turned out that other properties are also "opposite".)

notation:- if particle = \( P \), then antiparticle = \( \bar{P} \) ; often pronounced "P-bar"

**Neutral particles**

Neutral particles also have anti-particles, in some cases the particle and its anti particle are the same (majorana particles), in others they are different (dirac particles).

examples:-

charged: - electron\( (e^-)/\text{positron}(e^+) \),
proton\( (p)/\text{antiproton}(\bar{p}) \),
pions($\pi^+ / \pi^-$)

neutral
different (*Dirac*)
neutron(n)/antineutron($\bar{n}$),
kaons($K^0 / \bar{K}^0$)
same (*Majorana*)
photon, pion($\pi^0$)

Creation
Particle/anti-particle pairs can be created from energy, e.g. from that of a photon if its energy is greater than the total mass-energy of the pair of particles to be created. For example,

$$\gamma \Rightarrow e^+ + e^- \text{ if } E_\gamma > 1.22 \text{ MeV}$$

takes place near a nucleus which absorbs some momentum; necessary for energy and momentum conservation.

Annihilation
When a particle and its anti-particle meet, they annihilate and produce energy, for example

$$e^+ + e^- = \gamma + \gamma$$

This process needs to have at least two photons produced in order to conserve energy and momentum.

note:- $E_\gamma = hv$ and $p_\gamma = hv/c$

**Lepton number**: - conserved for each generation separately

(i.e total lepton number for each generation separately must remain constant in an interaction)

**Quark flavour number**:- conserved separately for each flavour in electromagnetic and strong interactions but not in weak interactions. Flavour must change when the W's are involved.

2.3.4 Fermions and Bosons

The terms fermions and boson describe the statistics of particles, i.e. how particles behave when put into a quantum system, for example:- electrons in a crystal or an atom, or quarks in a hadron, nucleons in a nucleus.

Fermions are particles which follow Pauli’s exclusion principle

"Two particles with the same quantum properties cannot occupy the same quantum state"
They also have half integer spin: - 1/2, 3/2, 5/2 .... The orientation of spin, as well as its magnitude, are quantum properties of particles. In quantum systems the orientations with respect to one another or with respect to some external influence (e.g. a magnetic field) is important. Two particles with the same magnitude of spin but different orientation have different quantum properties, so for example two otherwise identical quarks can coexist in the same nucleon; their spins point in opposite directions.

*All leptons, quarks and baryons are fermions*

Bosons are particle which do not obey the Pauli exclusion principle; all the bosons in a quantum system can occupy the same quantum state. They have integer spin: - 0, 1, 2, ...

*Mesons, and all the exchange particles are bosons.*

### 3. Nuclear transformations.

How does the standard model affect nuclear transformations, transmutations and decays?

#### 3.1. Alpha and gamma decays, fission and fusion are reactions at the nuclear level. The nucleons in a nucleus interact via the "strong nuclear force" mediated by (mostly) pi mesons.

Gamma decay, like photon emission from an atom, results from a nucleus going from a higher to a lower energy state. This could be one nucleon from one energy level to another or from a change in the collective motion of the nucleus as a whole.

Alpha decay is the emission of a preformed alpha particle (helium nucleus) from the parent nucleus. The process involves the alpha particle quantum tunnelling through the electrostatic potential barrier surrounding the parent nucleus. At the time, the ability of this model to predict the relationship between the energy of the emitted alpha and the lifetime for the decay was a triumph for the recently formulated quantum theory.

#### 3.2. Beta decay, on the other hand is a quark flavour change phenomenon.

At the nuclear level we write it as:-

\[
N^* (A,Z) \rightarrow N(A,Z-1) + \beta^+ + \nu_e \quad \text{beta-plus decay}
\]
\[
N^* (A,Z) \rightarrow N(A,Z+1) + \beta^- + \bar{\nu}_e \quad \text{beta-minus decay}
\]

At the nucleon level, the decay involves one nucleon, the other nucleons in the nucleus are spectators

\[
p \rightarrow n + \beta^+ + \nu_e \quad \text{beta-plus decay}
\]
\[
n \rightarrow p + \beta^- + \bar{\nu}_e \quad \text{beta-minus decay}
\]
The first of these decays can only occur within a nucleus, the second is also the fate of a free neutron. It decays with a mean life of 886 s (half life of 615 s).

At the quark level, one of the quarks changes flavour, the other quarks in the nucleon are again just spectators.

\[
u \rightarrow d + \beta^+ + v_e \quad \text{beta-plus decay}
\]

\[
d \rightarrow u + \beta^- + \bar{v}_e \quad \text{beta-minus decay}
\]

We can describe this in terms of exchange bosons. The u changes to a d with the emission of a \(W^+\), which decays into \(\beta^- + v_e\). The interaction takes such a short time and in such a small space that the uncertainty principle allows short term local variations in energy and momentum of the particles to cover energy and momentum conservation during the interaction. Once the dust has settled the total final energy and momentum of the particles must be the same as the initial energy and momentum.

After the decays, the daughter nuclei may be in another unstable state and another decay will take place.

Note:- the muon decays to an electron, neutrino and antineutrino

\[
\mu^- \rightarrow e^- + \bar{v}_e + \nu_{\mu}
\]

### 3.3 Competing interactions and decays.

In many cases, at the nuclear and fundamental particle level, the decays can occur in a number of different ways. This can be either between different energy levels or via different interactions. The rate, for each decay, is determined by circumstances and is reflected in the decay constant associated with each decay. Even rare decay modes
will occasionally take place. The total decay constant in these cases is the sum of the various decay constants.

A similar process can take place when a radioactive tracer is used in study of chemical take up in plants and animals. The radioactive compound is administered and radioactivity monitored. Often the chemical elimination process follows the traditional exponential decay form, ie a small, constant fraction of the tracer is eliminated in a given time interval. The elimination rate can then be calculated by

\[ \text{rate}_{\text{elimination}} = \text{rate}_{\text{total}} - \text{rate}_{\text{radioactive}} \]

An example is iodine-125 has a half-life of 60 days. Some is administered to the thyroid and the measured activity is found to have a half life of 17 days. Calculate the biological half-life of this isotope in the thyroid. The effective half life, as measured by the radioactivity of the thyroid is

\[ \frac{1}{T_{\text{eff}}} = \frac{1}{T_{\text{bio}}} + \frac{1}{T_{\text{phys}}} \]

ie \[ \frac{1}{T_{\text{bio}}} = \frac{1}{T_{\text{eff}}} - \frac{1}{T_{\text{phys}}} = \frac{1}{17} - \frac{1}{60} = 0.0422 \] so \( T_{\text{bio}} \) is about 24 days.

Another example of competing rare processes is the burning of hydrogen to helium in stars. The interior of a star, our sun for example, consists of ionised hydrogen at a temperature of about 10^7 degrees (mean thermal energy 1 keV). Even though at these energies most proton collisions are coulomb scattering, a compound nucleus can be produced consisting of 2 protons (the diproton). Most of the time this dissociates back into two protons, but rarely one of the protons decays to a neutron thus making a deuteron (d).

\[ p + p \rightarrow 2p \rightarrow d + \beta^+ + \nu_e \]

The deuteron is stable and eventually will combine with a proton to produce an excited state of He^3

\[ d + p \rightarrow \text{He}^3 + g \]

The He^3 is also stable and eventually two will combine in the nuclear reaction:

\[ \text{He}^3 + \text{He}^3 \rightarrow \text{He}^4 + p + p \]

Thus the net result is

\[ 4p \rightarrow \text{He}^4 + 2p + 2\beta^+ + 2\nu_e + Q \]

and from the mass values this releases an energy Q, about 28 MeV, which is eventually radiated by the star. The neutrinos emerge from the sun and their flux can be measured at the earth (eg Sudbury and Kamiokande experiments). The difference between the measured fluxes and those predicted from calculation of solar models is an indication of neutrino oscillation.

Classroom activity
The competing decay processes can be modelled in the classroom. A set of dice can be used. Throwing a "1" results in a radioactive decay and a "2" or "3" in chemical elimination. The remaining numbers leave the nucleus unaltered in the object. If a large number of dice are available the eliminated dice can be set aside. Alternatively the equivalent statistical model can be applied. A single dice is thrown for a definite nucleus until one of the "out" numbers appears. That nucleus is now out of the game and the next nucleus is now dealt with. Each throw counts as a time interval and so the decay rates can be calculated.

4 Production and detection of particles.

In the early days of the study of subatomic particles, the sources of those particles were rather ad-hoc. They might for example result from the heating of a filament to high temperature, or through obtaining pieces of radioactive material, or by examining the cosmic rays which bombard the Earth. With the invention and development of accelerators, certain types of charged particles could be formed into beams, steered using magnetic fields and accelerated to higher and higher energies using electric fields. These beams could then be made to collide either with a fixed target, or with each other, under controlled conditions.

Much of the progress in the understanding of both nuclear and particle physics and the creation of new types of particles has come from carefully designed experiments harnessed to ever-larger and higher energy particle accelerators. The state-of-the-art in this regard is the Large Hadron Collider (LHC) at CERN near Geneva, which after a number of years of construction is being completed at around the time of this workshop. The LHC will collide together beams of protons, with each proton possessing energy 7 TeV, about equivalent to the energy of motion of a handful of flying mosquitoes.

![Overall view of the LHC experiments.](image)

Schematic of the Large Hadron Collider and its four experiments. The large ring is 27km in circumference and lies between 50m and 150m below the surface. Image: copyright CERN

The passage of charged particles in matter is observed by the ionisation they produce. This ionisation can be collected at electrodes or observed by the ensuing light pulse in
some materials (scintillators). The energy of the particle is measured if it deposits all its energy in the detector. Its momentum is measured from its trajectory in a magnetic field. The energy can be derived from this if the identity of the particle is known (or assumed).

On the other hand neutral particles do not leave a track; we observe them only if they interact with something and produce a charged particle in the process, whose track we can then follow. The energy and momentum of the neutral particle is determined by making assumptions about the nature of the interaction and then applying conservation laws for energy and momentum. Often a number of particles are produced in the interaction and then the total energy and momentum of all particles must be measured in order to estimate the energy and momentum of the incident neutral particle.

Using these basic detection techniques, the sophistication of state-of-the-art particle detectors has evolved enormously over the past century. Starting from the simple photographic plates used by Roentgen in the discovery of X-rays, through Wilson’s cloud chamber used in the early detection of alpha and beta radiation, to the beautiful pictures of particle tracks produced by bubble chambers from the 1950s to 1980s, the complexity and scale of instruments designed to capture as much information as possible from the collisions or decays of subatomic particles has grown and grown.

Today, detectors are usually devices which record information electronically rather than by photographic image, with the most complex of all being the ATLAS and CMS detectors, each the size of a six storey building, which are now in place at CERN awaiting the first collisions of the LHC this year. The seeming contradiction that in order to learn about matter at the very tiniest scales it is necessary to build the largest scientific instruments ever constructed is one that can readily be explained in terms of quanta and the effective wavelength of the colliding particles, as we noted earlier.

The ATLAS detector at the Large Hadron Collider at CERN. Note the size of the human figures for scale. Image: copyright CERN.

5 Beyond the Standard Model.
Whilst the Standard Model gives an extremely good description of the fundamental particles and forces of nature as it is, the physics community is convinced that it is not the ultimate theory of nature but is, rather, a very good approximation to a deeper theory. There are a number of reasons for taking this point of view.

One of the things that physicists would like to know more about is the origin of mass. Before looking beyond the Standard Model, first note that in terms of experimental observation, there remains one missing piece of the present model, which is an elusive particle known as the Higgs boson. The Standard Model unifies the electromagnetic and weak forces into a single electroweak force, and in doing so provides an explanation of why the carrier of the electromagnetic force, the photon, is massless whereas the carriers of the weak force are not. The explanation requires the existence of one further massive particle, the Higgs, but does not predict exactly what its mass should be. Finding evidence for the Higgs has been the goal of a number of experiments to date, and is one of the main reasons for the building of the Large Hadron Collider. It is hoped that the higher energy collisions in the new collider will allow Higgs particles to be produced and studied.

The fact that the Standard Model cannot predict what the mass of the Higgs particle is leads us to the first reason for considering it incomplete. In total there are around twenty such “free parameters” in the model whose values are not predicted and must be measured by experiment. These include the masses of the quarks and fermions, and the strengths of the forces. Explaining why the neutrinos have such tiny masses in comparison to their charged lepton counterparts forms a part of the puzzle. A deeper theory would ideally have less free parameters in it and predict the sizes and relationships between some or all of those parameters in the current Standard Model.

As well as not having an explanation for the exact values of the masses of the quarks and leptons, the Standard Model also does not explain why there are three families of quarks and leptons. This remains one of the outstanding questions which a deeper theory needs to explain.

The unification of the various forces of nature has been a goal of physics for a long time, with the idea that less forces leads to a simpler theory. Maxwell unified electricity and magnetism in the 1800s, and the resulting electromagnetic force was unified with the weak force in the 1960s and 1970s and is one of the triumphs of the Standard Model. The strong force is incorporated in the Standard Model but not in a way which unifies it with the electromagnetic and weak forces.

The basic idea which drives unification of the forces is that at sufficiently high energies or temperatures, such as would have been the case in the first instants after the Big Bang, the strengths of the forces would have been effectively the same, and the fact that we observe them as being quite different is due to our living nowadays in a relatively cool Universe. To make this idea work in practice, one conjecture that has been put forward is that of Supersymmetry, which couples every known fermion with an as yet unseen boson and vice versa, effectively doubling the number of fundamental particles in nature. No experimental evidence for Supersymmetry has yet been uncovered.
There is of course one other force of which we are all very aware, and that is gravity. In comparison with the other forces it is actually very weak, and is not a part of the Standard Model. Treating gravity on the same level as the other forces, in a theory which unifies all of the known forces, is the goal of a large part of the present day research in theoretical physics. The Standard Model is a quantum theory and the theory of gravity, Einstein’s general relativity, is a classical theory, and the merging of the two is proving a very difficult problem. It has lead to huge efforts in areas known as quantum gravity and string theory. It is generally true to say that to date this effort has not lead to firm predictions which can be tested by experiment, although some of the ideas which come out of this research, such as the existence of extra dimensions beyond the three with which we are familiar, or the possible existence of mini-black holes, add to the excitement of what could possibly be found with the LHC experiments. Certainly these ideas grab the imagination of students and the general public.

There are other outstanding problems which it is hoped our understanding of can be improved with a deeper theory than the Standard Model. These include the question of why the Universe has an overwhelming abundance of matter over antimatter, whereas the amount of each should have been the same at the instant of the Big Bang. The Standard Model can incorporate an asymmetry between the behaviour of matter and antimatter but the amount of asymmetry in the Standard Model is nowhere near enough to explain the asymmetry observed in the present day Universe, which leads physicists to speculate on the need for additional particles and forces in nature which would have been important at the energies present in the early Universe but which are not apparent today.

Finally, current observation of the Universe has led to the idea that in order to explain its properties, most of the matter in it must be invisible to us, “dark matter”, and that the rate of expansion of the Universe is in fact increasing with time, which leads to the concept of “dark energy”. Finding new particles and interactions which could be candidates for explaining these two observations is something which particle physics aims to do. For example, if supersymmetry really does exist then the lightest new particle associated with that might provide an explanation of the dark matter.

The quest to understand the content of the Universe on its vast distance scales, and how it evolved following the Big Bang, is the realm of astronomy and cosmology. The quest to understand what happens at the very tiniest distance scales, which involves studying the behaviour of particles at very high energies, is the realm of particle physics. That these two seemingly different fields of endeavour are so intimately connected is a source of fascination for many, and the link is well worth establishing in students minds.

With the imminent turn-on of the LHC, many of these ideas of “physics beyond the Standard Model” are very topical and getting a lot of coverage in the popular media.

6 Further Resources.

Web-sites:-

Firstly, from a particle physics perspective, a very good site is:-
http://particleadventure.org/
In the U.S. there is a well-developed programme funded by the National Science Foundation and aimed at physics teachers and high school students, known as QuarkNet. The web site is:-

http://quarknet.fnal.gov

Resources including classroom activities can be found there.

CERN also has a web site and annual programme aimed directly at high school teachers, which also has a number of activities available:-

http://teachers.cern.ch/web/teachers/

In fact most particle physics and nuclear laboratories have general education sections at their web-sites and links to other useful sites. Three starting points are:-

http://cern.ch/   European Laboratory Geneva Switzerland
http://www.fnal.gov/   Fermi National Accelerator Laboratory USA
http://www2.slac.stanford.edu/vvc/   Stanford Linear Accelerator Laboratory USA

Some of the large experiments put a lot of effort into outreach programs to provide accessible information to the general public. An example of relevance to us here at the University of Sydney is the ATLAS experiment at the Large Hadron Collider at CERN.

http://atlas.ch/

From the nuclear physics perspective, an educational site worth mentioning is the ABCs of Nuclear Science, hosted by the Lawrence Berkeley Laboratory:-

http://www.lbl.gov/abc/

Further reading:-

*Facts and Mysteries in Elementary Particle Physics*  
Martinus Veltman  
World Scientific publishing, Singapore 2003  
isbn 981 238 149 x (pbk)

*Deep Down Things*  
Bruce A Schumm  
Johns Hopkins University Press, Baltimore2004  
isbn 0 8018 7971 x (hbk)

*Understanding the Universe, from Quarks to the Cosmos*  
Don Lincoln  
World Scientific publishing, Singapore 2004  
isbn 981 238 705 6 (pbk)

Also the general science magazines and journals.
NUCLEAR and PARTICLE PHYSICS: A SHORT HISTORY.

1895 X rays discovered by Roentgen.

1896 Henri Becquerel discovered radioactivity (beta from Th234 E_p=0.26 and 0.19 Mev. The parent U238 alpha decay E_α=4.19 Mev)

1896 Lorentz interprets Zeeman splitting as the motion of charged particles in atoms.

1897 Electron is discovered. The value of e/m of cathode rays measured; most carefully by Joseph Thomson (J.J.).

1899 J.J.Thomson also measures e-, establishing small value of m_e.

Ernest Rutherford publishes study showing that "Becquerel rays" have at least two components which he calls α (absorbed) and β (penetrating).

1900 Paul Villard discovers γ-rays as very penetrating radiation from "radium", evidence grows that radiation is similar to X-rays but not confirmed until 1914 when Rutherford reflects them from crystals.

1902 Rutherford and Soddy explain radioactivity as transmutation of the elements.

1905 Einstein paper "On the Electrodynamics of Moving Bodies" special relativity

1909 α particle identified as Helium nucleus

1911 Rutherford realises that reflection of a particle from gold foil means that the positive charge in an atom is concentrated in a very small region (r < 10^-13 m).

1920 Proton identified; named by Rutherford.

1923-30 Development of Quantum Mechanics

1923 Louis DeBroglie introduces wave-particle duality

1924 Bose-Einstein statistics

1925 Wolfgang Pauli proposes exclusion principle.

Werner Heisenberg wave mechanics

Intrinsic spin proposed Samuel Goudsmit and George Uhlenbeck

1926 Erwin Schroedinger wave equations

Fermi-Dirac statistics

1928 Dirac equation
α-decay as tunneling phenomenon proposed (Gamow, Gurney, Condon)

1924    Gustaf Ising proposes multiple traversal through potential difference to accelerate particles.

1929-32 Ernest Lawrence builds cyclotron.

1930    Pauli proposes neutrino hypothesis.

1931    Paul Dirac proposes positron.
        Robert Van de Graaff generates 1.5 MV

1932    Carl Anderson discovers positron.
        James Chadwick discovers neutron.
        Proton-neutron nucleus proposed by Heisenberg.
        John Cockroft and Ernest Walton produce first nuclear reaction using accelerator.

1934    Discovery of radiation induced radioactivity (Irene Curie and Jean Joliot).
        Theory of β-decay Enrico Fermi

1935    Hideki Yukawa proposes meson hypothesis and the concept of exchange of particles mediating force. (Meson or mesotron name given to particles with mass between $m_e$ and $m_p$. Now use this name for particular kind of strongly interacting bosons.)

1936    Mesotron detected (later turns out to be muon ~ heavy electron)
        Bohr proposed that a compound nucleus in formed in nuclear reactions.

1938    Nuclear fission discovered by Otto Hahn and Fritz Strassman

1939    Liquid drop model of nuclear fission, Bohr and Wheeler.

1940    First transuranium produced (McMillan and Seaborg).
        Pauli proposes connection between spin and statistics.

1941    First betatron, magnetic induction electron accelerator.

1942    Experiments on controlled fission by Enrico Fermi leading to development of fission bomb (1945) and power generation (1950's)

1946    Berkeley synchrotron operational (deuterons)
        Nuclear magnetic resonance (F. Bloch and E. Purcell)
        Development of radiocarbon dating (W. Libby)

1947    Cecil Powell identifies pion (meson) and muon (lepton) in emulsion as a decay: parent called π-meson and daughter called μ-meson
1947-50  V-particles observed in cosmic ray data later renamed as K-mesons and 'hyperons' (particles with mass > $m_{\text{neutron}}$)

1949  Shell model of nucleus proposed by Mayer, Jensen, Hexel Suess

1952  First thermonuclear (fusion) bomb.

1953  "Strangeness" hypothesis (Murray Gell-Mann, Kazuhiko Nishijima) and strange particles produced.

1955  Anti-proton discovered (O. Chamberlain, E. Segre, C. Wiegand, T. Ypsilantis)

1956  Neutrino detected from beta decay in reactors (Frederick Reines and Clyde Cowan)

1956  Parity violation observed in $^{60}$Co decay (Tsung Dao Lee, Chen Ning Yang, Chien-Shiung Wu et al)

1964  CP violation in $K^0$ decay (James Cronin and Val Fitch)

$$K^0/\bar{K}^0 \text{ decay}$$

$$K_i \rightarrow 2\pi^0 \text{ or } \pi^+ + \pi^-$$

$$K_j \rightarrow 3\pi^0 \text{ or } \pi^+ + \pi^- + \pi^0$$

1964  Quark model of hadrons proposed by Gell-Mann and independently by George Zweig.

1965  Introduction of "colour" quantum number, but all observed particles are colourless (Han and Nambu).

1967  Steven Weinberg and Abdus Salam achieve unification of electromagnetic and weak forces into a single "electroweak" theory.

1970  Sheldon Glashow adds a fourth quark (the charmed quark) to the quark model; to explain why certain reactions are not seen!

1971  Proton-proton collider at CERN.


The $J/\psi$ particle (meson) discovered confirming charm.

Burton Richter (J) and Samuel Ting ($\psi$).

1975  Martin Perl discovers the $\tau$-particle (tau); third generation of leptons.

1977  Leon Lederman discovers the upsilon (Y-particle = $b\bar{b}$; a meson); third generation of quarks inferred ($b$, $t$).

1983  Carlo Rubbia discovers the exchange particles for the weak force;
the W± (80 GeV/c²) and Z⁰ (91 GeV/c²).

1991 Upper limit on generations seems to be limited to 3;
(from decay rates of Z⁰)

1995 Top quark found at 179 ± 12 GeV/c²,
(at Fermilab Tevatron; CDF and D0 detectors).

2000+ Heaviest elements (Z 118, A 293, N 176) .. but only for a moment ...

Anti hydrogen atoms produced at CERN: Antiproton with positron.
Construction is underway of large hadron collider (LHC) at CERN. The
two oppositely directed hadron beams will cross at four places. At two of
these large detectors are being built; ATLAS at one and CMS at the
other. Australia is a part of the ATLAS collaboration.

An extensive array of cosmic ray detectors, called the Auger project, is
starting operation in Argentina. This is also an international
collaboration and Australia is a part of it. Eventually another array will
be built in the northern hemisphere.

There are strong indication of the existence of neutron and possibly
quark stars and work is under way on modelling these.

CP violation has been observed in the B-zero mesons (b and d quark
combinations)

Relativistic Heavy Ion Collider (RHIC) has started operation at
Brookhaven with four detectors.

Neutrino oscillation experiments have reported results indicating that not
all neutrinos in the three generations can be massless.

A number of new neutrino telescopes have been built and have reported
results; a couple of examples:-
IceCube which is a telescope, using one cubic kilometer of ice below the
surface of the South Pole as part of the detector designed to make images
of the universe using neutrinos.
AMANDA (Antarctic Muon and Neutrino Detector Array) is another
experiment in the antarctic ice to look for energetic neutrinos from
astronomical point sources.

Still looking for the Higgs particle and any evidence for any super
symmetric particles.

Still trying to unify the electroweak and strong forces.

Work on Nuclear Energy amplifiers and incineration of nuclear waste.