THE STANDARD MODEL OF MATTER

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.

Putting things into perspective

<table>
<thead>
<tr>
<th>Object</th>
<th>Size</th>
<th>Break up energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand grain</td>
<td>1 mm</td>
<td></td>
</tr>
<tr>
<td>Virus</td>
<td>100 nm (10^{-7} m)</td>
<td>1 meV</td>
</tr>
<tr>
<td>Atom</td>
<td>100 pm (10^{-11} m)</td>
<td>10 eV</td>
</tr>
<tr>
<td>Nucleus</td>
<td>10 fm (10^{-14} m)</td>
<td>8 MeV</td>
</tr>
<tr>
<td>Nucleon</td>
<td>1 fm (10^{-15} m)</td>
<td></td>
</tr>
<tr>
<td>Quark</td>
<td>&lt; 1 am (10^{-18} m)</td>
<td></td>
</tr>
</tbody>
</table>

The nature of the atom was established in 1911 by Rutherford's experiments on the scattering alpha particles off thin gold films. There were more large angle scattering than expected from the gold atoms in which the positive and negative charges were assumed to be spread out over the whole atom. The implication of the scattering experiments was that an atom had a small positive nucleus so that its strong electric field could deflect the alpha particles. Thus, an atom consists of a small heavy central positive nucleus surrounded by electrons with most the atom being simply empty space.

Exercise

Calculate how energetic must an alpha particle be in order to reach the surface of a gold nucleus in a head on collision.

\[
(R_{\text{nucleus}} = 1.23 A^{1/3} \text{ fm} \quad A_{\text{gold}} = 200 \quad \text{ans: } E_{\text{alpha}} \sim 31 \text{ MeV})
\]

To investigate the structure of matter, high energy projectiles from an accelerator are smashed into a target. High energies are required for two reasons.

1. The projectiles must have very short deBroglie wavelengths as the wavelength of the matter wave needs to about the same order of magnitude of the dimensions to be investigated in the target.

2. The incident particles must have enough energy to produce new particles in the collision of the constituents of the target.
From experiments using accelerators many **elementary particles** other than the electron, proton and neutron have been discovered.

The most widely accepted theory of elementary particles at present is the **Standard Model**.

All matter consists of:
- **Fermions** which exert attractive or repulsive forces on each other.
- **Gauge bosons** which are force-mediating particles exchanged between fermions.

There are two varieties of **fermions** both of which are divided into three generations:
- **Leptons** are essentially point-like fundamental particles.
- **Quarks** maybe also point-like ($< 10^{-18}$ m) and are always found confined together and never as isolated particles in a free state. Quarks make up particles called **hadrons**.

Everything from galaxies to mountains to molecules is made from fermions (quarks and leptons). But that is not the whole story. Quarks behave differently to leptons.

**ANTI-MATTER**

For every type of matter particle, there also exists a corresponding **anti-matter** particle, or antiparticle. Anti-particles look and behave just like their corresponding matter particles, except they have opposite charges. For instance, a proton is electrically positive whereas an anti-proton is electrically negative. The **positron** is the anti-particle of the electron.

Gravity affects matter and anti-matter the same way because gravity only depends upon the masses of particles and not their charges. The usual symbol for an anti-particle is a bar over the corresponding particle symbol, e.g., the neutrino $\nu$ and the anti-neutrino $\bar{\nu}$. When a matter particle and anti-matter particle meet, they annihilate into pure energy with the emission of two photons. The idea of anti-matter is strange, made all the stranger because the universe appears to be composed entirely of matter, and nobody knows why! Anti-matter seems to go against everything you know about the universe.

**Creation**

Particle / anti-particle pairs can be created from energy, e.g., a photon if its energy is greater than the total mass-energy of the pair of particles created. For example an electron / positron pair can be created near the nucleus which absorbs some momentum so that momentum can be conserved

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

**Annihilation**

When a particle and its anti-particle meet, they annihilate and produce energy, e.g.,

$$e^+ + e^- \rightarrow \gamma + \gamma$$

Need to have at least two photons produced to conserve energy and momentum

$$E_\gamma = hf \quad p_\gamma = hf/c$$
Fermions and bosons
The terms fermions and bosons describe the statistics of particles, i.e., how particles behave in a quantum system, for example, electrons in a crystal or an atom; quarks in a hadron; and nucleons in a nucleus.

Fermions are particles that obey the Pauli Exclusion Principle

Two particles in a quantum system can’t occupy the same quantum state

Fermions have a property called spin and the orientation of the spin together determines their behaviour in quantum systems, for example, in an external magnetic field. The spin for fermions always have a half integer value of 1/2 or 3/2 or 5/2, ... . Two particles with the same magnitude of spin but different spin orientations have different quantum properties, so for example, two otherwise identical quarks can coexist in the same nucleon with their spins pointing in opposite directions and two electrons can exist together in a 1s subshell.

Bosons are particles that do not obey the Pauli Exclusion Principle and have zero or integer spins (0, 1, 2, ... ). An unlimited number of bosons can co-exist simultaneously in the same quantum state.

The Standard Model is a good theory. Experiments have verified its predictions to incredible precision, and all the particles predicted by this theory have been found. But it does not explain everything:

- Gravity is not included in the Standard Model.
- The Standard Model in itself does not predict particles masses. It is believed that the Higgs boson may be the key to understanding the mystery of particle masses.
- Why are there only three generations or families of fundamental particles?
- Do quarks and leptons actually consist of more fundamental particles?

The everyday world of atoms and molecules are made up of only the first generation quarks and leptons, the first generation antiparticles and higher generations only make fleeting appearances with a couple of exceptions e.g., the positron and the electron antineutrino. 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.
BOSONS – force carrier particles

The Standard Model asserts that the forces governing the interaction of quarks and leptons can be understood by using the quantum mechanics of fields. Quantum field theory suggests that forces between particles are due to the exchange of special force-carrying particles called gauge bosons. Bosons are particles which do not obey the Pauli Exclusion Principle, all the bosons in a quantum system can occupy the same quantum state.

Force carrier particles – gauge bosons (graviton, photon, gluon, W⁺ W⁻ Z⁰)

In the Standard Model of Matter there are four fundamental forces.

- **Gravitational force**: a long-range force acting on all masses in the universe. It is the weakest of all the forces. It is believed to be carried by the graviton, which has not yet been observed experimentally.
- **Electromagnetic force**: a long-range force that acts on all charges in the universe. It holds atoms and molecules together. It is carried by the photon.
- **Strong nuclear force**: holds protons and neutrons together in the nucleus. It is a short-range force operating at nuclear distances (~10⁻¹⁵ m). In the Standard Model, it also binds quarks together and is carried by the gluon.
- **Weak nuclear force**: interaction between particles such as electrons to change them into other forms. It is short-ranged (~10⁻¹⁷ m). It is responsible for beta decay. In the Standard Model it also transforms one quark type into another and is carried by the W⁺, W⁻ and Z⁰ bosons.

<table>
<thead>
<tr>
<th>Force</th>
<th>Exchange boson</th>
<th>&quot;charge&quot;</th>
<th>Range</th>
<th>Mass m / m₀</th>
<th>Relative Strengh</th>
<th>No. of types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitation</td>
<td>graviton</td>
<td>Mass</td>
<td>infinite</td>
<td>0</td>
<td>10⁻³⁹</td>
<td>1</td>
</tr>
<tr>
<td>Weak nuclear</td>
<td>W⁺ W⁻ Z⁰</td>
<td>Weak</td>
<td>~10⁻¹⁸ m</td>
<td>~ 90</td>
<td>10⁻⁹</td>
<td>3</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photon</td>
<td>Electric</td>
<td>infinite</td>
<td>0</td>
<td>10⁻²</td>
<td>1</td>
</tr>
<tr>
<td>Strong nuclear</td>
<td>gluon</td>
<td>Colour</td>
<td>~10⁻¹⁵ m</td>
<td>0</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

Which particles “feel” forces

<table>
<thead>
<tr>
<th>Particle</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>Z⁰</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>

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 arises 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.
There are six leptons pairs (particle / antiparticle), three pairs of which have an electrical charge and three pairs of which do not. They appear to be point-like particles without internal structure. The best known lepton is the electron $e$. The other two charged leptons are the muon $\mu$ and the tau $\tau$, which are charged like electrons but are much more massive. The other leptons are the three pairs of neutrinos $\nu$.

Neutrinos have zero electrical charge, very little mass, and they are very hard to find. Note that the antielectron has a special name, the positron. Leptons do not experience the strong force and interact through the weak nuclear force and the electromagnetic force if they are charged.

<table>
<thead>
<tr>
<th>LEPTON FLAVOUR</th>
<th>PARTICLE (charge)</th>
<th>ANTIPARTICLE (charge)</th>
<th>MASS (MeV/c$^2$)</th>
<th>Lifetime (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$ (+e)</td>
<td>positron $e^+$ (+e)</td>
<td>0.511</td>
<td>stable</td>
</tr>
<tr>
<td>Electron-neutrino</td>
<td>$\nu_e$ (0)</td>
<td>$\bar{\nu}_e$ (0)</td>
<td>&lt; 3x10$^{-6}$</td>
<td>stable</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu$ (-e)</td>
<td>$\bar{\mu}$ (+e)</td>
<td>105.7</td>
<td>2.2x10$^{-6}$</td>
</tr>
<tr>
<td>Muon-neutrino</td>
<td>$\nu_\mu$ (0)</td>
<td>$\bar{\nu}_\mu$ (0)</td>
<td>&lt; 0.19</td>
<td>stable</td>
</tr>
<tr>
<td>Tau</td>
<td>$\tau$ (-e)</td>
<td>$\bar{\tau}$ (+e)</td>
<td>1777</td>
<td>2.9x10$^{-13}$</td>
</tr>
<tr>
<td>Tau-neutrino</td>
<td>$\nu_\tau$ (0)</td>
<td>$\bar{\nu}_\tau$ (0)</td>
<td>&lt; 18.2</td>
<td>stable</td>
</tr>
</tbody>
</table>

* mass of proton 938.3 MeV/c$^2$  mass of neutron 939.6 MeV/c$^2$

The mass of the neutrinos are uncertain and maybe zero, however evidence gathered over recent years of neutrino oscillations (neutrinos in flight changing generations or flavours) requires that in at least one of the generation neutrinos must have mass. Nevertheless it is still very small.

There are three generations of leptons:

<table>
<thead>
<tr>
<th>1$^{\text{st}}$</th>
<th>2$^{\text{nd}}$</th>
<th>3$^{\text{rd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$\mu$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
<td>$\nu_\tau$</td>
</tr>
</tbody>
</table>

The second and third generations charged leptons (muons and taus) are unstable and decay to lower generations. The electron hasn't anywhere to decay to. The heavier leptons, the muon $\mu$ and the tau $\tau$, are not found in ordinary matter at all. This is because when they are produced they quickly decay or transform into lighter leptons. Sometimes the tau lepton will decay into a quark – antiquark pair and a tau neutrino. For example, the muon decays into an electron and two neutrinos

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Electrons and the three kinds of neutrino pairs are stable and the types we commonly see around us. In all interactions the number of each type of lepton is conserved.
Quarks are one type of matter particle. Most of the matter we see around us is made from protons and neutrons, which are composed of quarks. There are six quarks / antiquark pairs, but physicists usually talk about them in terms of pairs: up/down, charm/strange, and top/bottom. Also, for each of these quarks, there is a corresponding antiquark.

The quarks combine to form particles called **hadrons** (particles which can feel the strong force).

There are two distinct types of hadrons:

- **Baryons** - three quarks or three anti-quarks
- **Mesons** - a quark/anti-quark pair

<table>
<thead>
<tr>
<th>QUARK FLAVOUR</th>
<th>SYMBOL</th>
<th>CHARGE</th>
<th>MASS (MeV/c²)</th>
<th>( m_{\text{quark}} / m_{\text{proton}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>( u )</td>
<td>(+2/3) e</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Down</td>
<td>( d )</td>
<td>(-1/3) e</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Strange</td>
<td>( s )</td>
<td>(-1/3) e</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>Charm</td>
<td>( c )</td>
<td>(+2/3) e</td>
<td>1250</td>
<td>1.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>( b )</td>
<td>(-1/3) e</td>
<td>4500</td>
<td>4.8</td>
</tr>
<tr>
<td>Top</td>
<td>( t )</td>
<td>(+2/3) e</td>
<td>175000</td>
<td>187</td>
</tr>
<tr>
<td>Up</td>
<td>( \bar{u} )</td>
<td>(-2/3) e</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Down</td>
<td>( \bar{d} )</td>
<td>(+1/3) e</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Strange</td>
<td>( \bar{s} )</td>
<td>(+1/3) e</td>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>Charm</td>
<td>( \bar{c} )</td>
<td>(-2/3) e</td>
<td>1250</td>
<td>1.3</td>
</tr>
<tr>
<td>Bottom</td>
<td>( \bar{b} )</td>
<td>(+1/3) e</td>
<td>4500</td>
<td>4.8</td>
</tr>
<tr>
<td>Top</td>
<td>( \bar{t} )</td>
<td>(-2/3) e</td>
<td>175000</td>
<td>187</td>
</tr>
</tbody>
</table>

The light quark masses are not well defined. They are strongly bound to each other and a single quark can never be experimentally isolated for a measurement.

Quarks have the unusual characteristic of having a **fractional electric charge**, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called **colour charge**. Quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called **hadrons**. Although individual quarks have fractional electrical charges, they combine such that hadrons have a net integer electric charge. Another property of hadrons is that they have **zero colour charge** even though the quarks themselves carry colour charge.

The name quark and the idea that protons, neutrons and other particles were composed of quarks was made by the American physicist, Murray Gell-Mann and he won the 1969 physics Noble Prize.
The properties of the interaction between quarks are described by a theory called quantum chromodynamics. The equivalent of electric charge for electrical forces is called colour charge for the strong nuclear force. Whereas in electrodynamics there are two charges, + and -, there are three colour charges; red (R), green (G) and blue (B). The idea of colour charge is needed in order to explain why baryons can contain three otherwise identical quarks. For a hadron, the three colour charges when added together must produce white as hadrons have to be colourless.

**Antiquarks possess anticolour:**
- antired (\(\bar{R}\)) = white - red = cyan
- antigreen (\(\bar{G}\)) = white – green = magenta
- antiblue (\(\bar{B}\)) = white – blue = yellow

**Baryons** contain three quarks, each quark a different colour, hence:
- \(R + G + B\) gives W (white), i.e., zero colour charge.

**Antibaryons**, containing three antiquarks are also colourless.
- cyan + magenta + yellow = white – red + white – green + white – yellow = white (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
  - cyan + red = white – red + red = white \(\Rightarrow\) colourless (zero colour).

**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.

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. 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 (i.e. travelled 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.
Baryons

3 quark combinations (qqq). All baryons interact through the strong force. The lightest and most stable baryons are the proton (uud) and neutron (udd).

![Proton (uud) and Neutron (udd)](image)

The existence of quarks has been well established by experimentation. When high energy electron beams are used to probe the proton or neutron for instance, three distinct scattering centres are found inside each particle. For example, in the 1960's experiments like the Rutherford scattering of alpha particles from gold atoms were performed but this time with high energy electrons were scattered off protons. The results also produced larger deflections then was 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 spaces (such as point like quarks).

In all interactions, the total baryon number is conserved.

There are many different hadrons that have been created when sub-atomic particles with high energies are smashed into each other. Some examples are (mass of particle in MeV/c^2 is shown in brackets):

Proton p (938.3), neutron n (939.6), Λ^0 (1116), Σ^+ (1189), Σ^0 (1193), Σ^- (1197)
Mesons

2 quark combinations (q\overline{q}). Mesons consist of a quark and an anti-quark pair and interact through the strong nuclear force.

One example of a meson is a pion \( \pi^+ \) (u\overline{d}) which is made of an up quark and a down antiquark. The antiparticle of a meson just has its quark and antiquark switched, so an antipion \( \pi^- \) is made of a down quark and an up antiquark (\overline{ud}).

Mesons are unstable because they consist of a particle and an antiparticle and often decay in millionths of a second to produce other particles such as photons, electrons and neutrinos.

There are many different mesons that have been created when sub-atomic particles with high energies are smashed into each other. Some examples are (mass if particle in MeV/c^2 is shown in brackets):

\( \pi^0 \) (135.0), \( \pi^+ \) (139.6), \( \pi^- \) (139.6), \( K^+ \) (493.7), \( K^- \) (493.7), \( \eta^0 \) (547.3)

All mesons are bosons.
Beta decay

Beta decay, is a quark flavour change phenomenon.

At the nuclear level we write it as

\[ ^A X_z \rightarrow ^A Y_{z+1} + e^+ + \nu_e \quad \text{element } X \rightarrow \text{element } Y \]

\[ ^A X_z \rightarrow ^A V_{z+1} + e^- + \bar{\nu}_e \quad \text{element } X \rightarrow \text{element } V \]

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

\[ ^P \rightarrow n + e^+ + \nu_e \]

\[ n \rightarrow ^P + e^- + \bar{\nu}_e \]

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 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.

\[
\begin{align*}
\text{proton:} & \quad d (-1/2) \\
              & \quad u (+2/3) \\
              & \quad u (+2/3) \\
\text{neutron:} & \quad d (-1/3) \\
               & \quad u (+2/3) \\
               & \quad d (-2/3)
\end{align*}
\]

\[ u \rightarrow d + e^+ + \nu_e \]

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

We can describe this in terms of exchange bosons. The u changes to a d with the emission of a \( W^+ \), which decays into \( e^+ \) and \( \nu_e \). 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, but, 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.
Web-sites

http://particleadventure.org/particleadventure/

http://cem.ch  European Laboratory Geneva Switzerland

http://www.foal.gov/  Fermi National Accelerator Laboratory USA

http://www2.slac.stanford.edu/wc/  Stanford Linear Accelerator Laboratory USA
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895</td>
<td>X rays discovered by Roentgen</td>
</tr>
<tr>
<td>1896</td>
<td>Henri Becquerel discovered radioactivity (beta from $^{234}\text{Th}$ $E_β = 0.26$ and $0.19$ MeV. The parent $^{238}\text{U}$ alpha decay $E_α = 4.19$ MeV)</td>
</tr>
<tr>
<td>1896</td>
<td>Lorentz interprets Zeeman splitting as the motion of charged particles in atoms</td>
</tr>
<tr>
<td>1897</td>
<td>Electron is discovered. The value of $e/m$ of cathode rays measured by J.J. Thomson</td>
</tr>
<tr>
<td>1899</td>
<td>J.J. Thomson also measures $e^-$, establishing small value of $m_e$. Ernest Rutherford publishes study showing that &quot;Becquerel rays&quot; have at least two components which he calls a (absorbed) and b (penetrating)</td>
</tr>
<tr>
<td>1900</td>
<td>Paul Villard discovers $γ$ rays as very penetrating radiation from &quot;radium&quot;, evidence grows that radiation is similar to X-rays but not confirmed until 1914 when Rutherford reflects them from crystals</td>
</tr>
<tr>
<td>1902</td>
<td>Rutherford and Soddy explain radioactivity as transmutation of the elements</td>
</tr>
<tr>
<td>1905</td>
<td>Einstein paper &quot;On the Electrodynamics of Moving Bodies&quot; Special Relativity</td>
</tr>
<tr>
<td>1909</td>
<td>$α$ particle identified as Helium nucleus</td>
</tr>
<tr>
<td>1911</td>
<td>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 ($r &lt; 10^{-13}$ m)</td>
</tr>
<tr>
<td>1920</td>
<td>Proton identified; named by Rutherford</td>
</tr>
<tr>
<td>1923-30</td>
<td>Development of Quantum Mechanics</td>
</tr>
<tr>
<td>1923</td>
<td>Louis deBroglie introduces wave-particle duality</td>
</tr>
<tr>
<td>1924</td>
<td>Bose-Einstein statistics</td>
</tr>
<tr>
<td>1925</td>
<td>Wolfgang Pauli proposes Exclusion Principle Werner Heisenberg wave Mechanics Intrinsic spin proposed Samuel Goudsmit and George Uhlenbeck</td>
</tr>
<tr>
<td>1926</td>
<td>Erwin Schroedinger wave equations Fermi-Dirac statistics</td>
</tr>
<tr>
<td>1928</td>
<td>Dirac equation $α$ decay as tunnelling phenomenon proposed (Gamow, Gurney, Condon)</td>
</tr>
<tr>
<td>1929-32</td>
<td>Ernst Lawrence builds cyclotron</td>
</tr>
<tr>
<td>1930</td>
<td>Pauli proposes neutrino hypothesis</td>
</tr>
</tbody>
</table>
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 $\beta$ decay Enrico Fermi

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

1936  Meson detected (later turns out to be muon - a lepton – 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 $\pi$ meson and daughter called $\mu$ 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  Antiproton 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)
Quark model of hadrons proposed by Gell-Mann and independently by George Zweig
W$^-$ minus observed

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 an 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

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

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

1983  Carlo Rubbia discovers the exchange particles for the weak force: the $W^+$ & $W^-$ (80 GeV/c$^2$) and, $Z^0$ (91 GeV/c$^2$)

1991  Upper limit on generations seems to be limited to 3: from decay rates of $Z^0$

1995  Top quark found at (179 ± 12 GeV/c$^2$) at Fermilab Tevatron accelerator

2000+  Heaviest elements (Z = 118  A = 293  N = 176 - but only for a moment ...)
Antihydrogen atoms produced at CERN: Antiproton with positron

Construction is underway of large hadron collider 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 observed in B-zero mesons (b and d quark combinations)

Relativistic Heavy Ion Collider 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: (1) IceCube which is a telescope, using one cubic kilometre of ice below the surface of the South Pole as part of the detector designed to make images of the universe using neutrinos. (2) AMANDA (Antarctic Muon and Neutrino Detector Array) another experiment in the Antarctic ice to look for energetic neutrinos from astronomic point sources.

2012 Possible evidence for the Higgs particle

Adapted from Dr Juris Ulrichs notes on Quanta to Quarks, Science Teachers Workshop, School of Physics, University of Sydney, 2006