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 Gamma with $\lambda \sim$ size</th>
<th>Energy to &quot;break up&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>grain, 1 mm</td>
<td>12 eV</td>
<td>1 meV</td>
</tr>
<tr>
<td>virus, 100 nm</td>
<td>12 keV</td>
<td>10 eV</td>
</tr>
<tr>
<td>atom, 100 pm</td>
<td>120 MeV</td>
<td>8 MeV</td>
</tr>
<tr>
<td>nucleus, 10 fm</td>
<td>1.2 GeV</td>
<td></td>
</tr>
<tr>
<td>nucleon, 1 fm</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 (light) were scattered off a gold nucleus (heavy). There were more large angle scattering than expected from an object in which the charge was spread out over the whole atom and 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 must an alpha particle 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. ($r_{\text{nucleus}} = 1.23 \text{ fm} \ A^{1/3}$, ans:- $E_{\text{alpha}} \sim 31 \text{ MeV}$)

In 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 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).

These are example 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 projectiles 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 energy > 10 mc^2, the wavelength is about the same as for a photon of the same energy, ie 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 follows a line in the n/p diagram, which become 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 (eg 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, molecules are 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 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), starting with:

12 leptons/anti-leptons, in 3 generations.

a) leptons

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge</th>
<th>mass MeV/c^2</th>
<th>mass m/m_{proton}</th>
<th>lepton number</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>ν_e</td>
<td>0</td>
<td>~0</td>
<td>0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>mu-minus</td>
<td>µ^-</td>
<td>-e</td>
<td>105.66</td>
<td>0.1126</td>
<td>0 1 0</td>
</tr>
<tr>
<td>mu-neutrino</td>
<td>ν_µ</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 1 0</td>
</tr>
<tr>
<td>tau-minus</td>
<td>τ^-</td>
<td>-e</td>
<td>1777</td>
<td>1.894</td>
<td>0 0 1</td>
</tr>
<tr>
<td>tau-neutrino</td>
<td>ν_τ</td>
<td>0</td>
<td>~0</td>
<td>0</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 MeV/c^2</th>
<th>mass m/m_{proton}</th>
<th>lepton number</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>ν_e</td>
<td>0</td>
<td>~0</td>
<td>0</td>
<td>-1 0 0</td>
</tr>
<tr>
<td>mu-plus mu-bar</td>
<td>µ^+</td>
<td>+e</td>
<td>105.66</td>
<td>0.1126</td>
<td>0 -1 0</td>
</tr>
<tr>
<td>muon antineutrino</td>
<td>ν_µ</td>
<td>0</td>
<td>~0</td>
<td>0</td>
<td>0 -1 0</td>
</tr>
<tr>
<td>tau-plus tau-bar</td>
<td>τ^+</td>
<td>+e</td>
<td>1777</td>
<td>1.894</td>
<td>0 0 -1</td>
</tr>
<tr>
<td>tau antineutrino</td>
<td>ν_τ</td>
<td>0</td>
<td>~0</td>
<td>0</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 anywhere to decay to.

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

Note1
The light quark masses are not well defined. They are strongly bound to each other; bare quarks can never 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 a another quark/anti-quark pair is created. This always present strong binding makes it difficult to determine its mass. ($m_{proton} = 938.3$ MeV/$c^2 = 1.673 \times 10^{-27}$ kg = 1.0073 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 GeV/$c^2$</th>
<th>mass $m/mp$</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>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></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 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.

**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 derWaals 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 quarks 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 π meson

$$\Delta^{++}(uuu) \rightarrow p(uud) + \pi^+(d,u)$$

**Note 5**
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.

**Antiquarks possesses anticolour:-**

- Antired (R̄) = white - red = cyan
- Antigreen (Ḡ) = white - green = magenta
- Antiblue (B̄) = white - blue = yellow

Quarks can not possess anticolour and antiquarks can not 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(R̄) 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 $(\nu_e, e^-)$ quarks $(u, d)$

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

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

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 quark/antiquark pair and baryons have three quarks.

2.3.3 Particles and antiparticles

Particle and its antiparticle have exactly the same mass but have opposite values for quantum numbers (originally this was charge only but. later turns out other properties are also "opposite").

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

Neutral particles
Neutral particle 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−)/positron(e+),
  proton(p)/antiproton(\overline{p})
  pions(π+/π−)
  neutral
  different (Dirac)
  neutron(\overline{n})/antineutron(\overline{n}),
  kaons(K^0/\overline{K^0})
  same (Majorana)
  photon, pion(π^0)

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

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

takes place near the 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. Eg

\[ e^+ + e^- = \gamma + \gamma \]

need 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
(ie 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, ie 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 can not 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 (eg 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 boson 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, 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) pimesons.

Gamma decay, like photon emission from an atom, results from 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. 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:

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

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

\[
\begin{align*}
p &\rightarrow n + \beta^+ + \nu_e & \text{beta-plus decay} \\
n &\rightarrow p + \beta^- + \bar{\nu}_e & \text{beta-minus decay}
\end{align*}
\]
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.

\[
\begin{align*}
\text{proton} & \quad \text{neutron} \\
\text{d} & \quad \text{d} \\
\text{u} & \quad \text{d} \\
\text{u} & \quad \text{d} \\

W^+ & \quad \rightarrow \beta^+ \\
& \quad \rightarrow \nu_e \\

u & \rightarrow d + \beta^+ + \nu_e \quad \text{beta-plus decay}
\end{align*}
\]

\[
\begin{align*}
\text{neutron} & \quad \text{proton} \\
\text{d} & \quad \text{d} \\
\text{u} & \quad \text{u} \\
\text{d} & \quad \text{u} \\

W^- & \quad \rightarrow \beta^- \\
& \quad \rightarrow \bar{\nu}_e \\

d & \rightarrow u + \beta^- + \bar{\nu}_e \quad \text{beta-minus decay}
\end{align*}
\]

We can describe this in terms of exchange bosons. The u changes to a d with the emission of a \(W^+\), which decays into \(\beta^+ + \nu_e\). 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. 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 and two neutrinos

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

### 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, i.e. 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

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

i.e

\[
1/T_{\text{bio}} = 1/T_{\text{eff}} - 1/T_{\text{phys}} = 1/17 - 1/60 = 0.0422 ; \text{so } T_{\text{bio}} \text{ is about } 24 \text{ days.}
\]

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 dissociated back into two protons, but rarely one of the protons decays to a neutron thus making a deuteron (d).

\[
p + p => 2p => d + \beta^+ + \nu_e
\]

The deuteron is stable and eventually will combine with a proton to produce an excited state of He3

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

The He3 is also stable and eventually two will combine in the nuclear reaction:-

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

Thus the net result is

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

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 (e.g. 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 **Detection of particles.**

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 the 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.

**Web-sites**

A very good site is http://particleadventure.org/particleadventure/

Most particle physics and nuclear laboratories have education sections at their websites 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
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, Baltimore 2004
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 $E_b=0.26$ and 0.19 Mev. The parent U238 alpha decay $E_a=4.19$ 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 a (absorbed) and $b$(penetrating).

1900 Paul Villard discovers g-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 a 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 machanics

1926 Intrinsic spin proposed Samuel Goudsmit and George Uhlenbeck

1926 Erwin Schroedinger wave equations

1928 Fermi-Dirac statistics

1928 Dirac equation

$\alpha$-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


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 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 - 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 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)

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

\[ K_1 \Rightarrow 2p^0 \text{ or } p^+ + p^- \]
\[ K_2 \Rightarrow 3p^0 \text{ or } p^+ + p^- + p^0 \]

1964 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 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 (y).
1975 Martin Perl discovers the t-particle (tau); third generation of leptons.
1977 Leon Lederman discovers the upsilon (U-particle = $\bar{b}b$; a meson) ;
third generation of quarks inferred ($b$, $t$).
1983 Carlo Rubbia discovers the exchange particles for the weak force; the $W^\pm$ ($80 \text{ GeV/c}^2$) and $Z^0$ ($91 \text{ GeV/c}^2$).
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 observed in 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) another
experiment in the antarctic ice to look for energetic neutrinos from
astronomic point sources.

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

Still trying to unify electroweak and strong forces.

Work on Nuclear Energy amplifiers and incineration of nuclear waste.