Quanta to Quarks

Science Teachers Workshop 2010
Workshop Session
Kevin Varvell
Quanta to Quarks

• Quantum, atomic, and sub-atomic physics; three parallel, yet strongly interacting topics
• We will look mostly at the last part today, concentrating on the “Standard Model”
• Highlight main points and look at some of the background.
• Examine some web resources
Inward bound

object and size

- grain, 1 mm \((10^{-3} \text{ m})\)
- virus, 100 nm \((10^{-7} \text{ m})\)
- atom, 100 pm \((10^{-10} \text{ m})\)
- nucleus, 10 fm \((10^{-14} \text{ m})\)
- nucleon, 1 fm \((10^{-15} \text{ m})\)
- quark, <1 am \((10^{-18} \text{ m})\)

From DESY site
The Atomic Level

Bohr model
• A mixture of classical and quantum physics

From http://astronomyonline.org/
Nuclear Level

Heisenberg model of nucleus

Nucleus:

- Z protons  (atomic number)
- N neutrons

Total

A = Z + N  (mass number)

nucleons

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Online Table of Nuclides

Interactive site giving a wealth of information on atomic nuclei

http://atom.kaeri.re.kr/
ABCs of Nuclear Science

Lawrence Berkeley Lab site in the U.S.

http://www.lbl.gov/abc/
The Standard Model (SM) describes the Universe in terms of a set of different kinds of particles and the interactions between them.

- **12 particles** (and their 12 antiparticles)
  - 6 leptons and their 6 antileptons
  - 6 quarks and their 6 antiquarks

- **4 interaction forces**:
  - gravity (not in SM), electromagnetic
  - weak, *fundamental* strong
The Standard Model

Plus an undiscovered Higgs boson?
The Particle Adventure

Excellent self-guided tour of particle physics

http://particleadventure.org
QuarkNet

U.S. initiative aimed at high schools

http://quarknet.fnal.gov/
HST

CERN initiative aimed at High School Teachers

High School Teachers at CERN

http://teachers.web.cern.ch/teachers/
How can we examine small objects?

By the light or particles they emit or scatter.

For very small objects the wavelength of the light or particle plays an important role.
Scattering – wavelength dependence

Diffraction of waves

Note that spread of pattern depends on $\lambda/a$:

For $\lambda < a$ a pattern depends on structure of object.

For $\lambda > a$ a pattern independent of structure of object
Particle diffraction

Similar diffraction behaviour is observed for scattering of electrons, neutrons by nuclei and crystals etc.

Wavelength of particle given by the *de Broglie* relationship:-

\[
\lambda = \frac{h}{p} = \frac{hc}{\sqrt{E_T^2 - m^2 c^4}}
\]

e.g. A 1GeV electron has a wavelength (1.23 fm) about the same as the diameter of a nucleon.

( note:- for \(E_T \gg mc^2\), \(\lambda = \lambda\) photon with same \(E_T\) )
Accelerators

CERN

Large Hadron Collider (LHC)

pp

3.5TeV+3.5TeV

(eventually 7TeV+7TeV)

27 km circumference
Accelerators

CERN

LHC

Tunnel

CERN Photo
CERN
The European Centre for Particle Physics

http://cern.ch
ATLAS Experiment at CERN

One of the two large experiments at the Large Hadron Collider

http://atlas.ch
Visualization of particle tracks (then)

Wilson cloud chamber

Bubble chamber
Visualization of particle tracks (now)

Electronic detectors

http://belle.kek.jp/evdisp/ (live)
HYPATIA

Analyse Large Hadron Collider Interactions

http://hypatia.phys.uoa.gr/

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Interactions.org
Up-to-date news and information on particle physics

http://www.interactions.org/
Extra Material
# the leptons – charge and mass

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge</th>
<th>$\text{MeV}/c^2$</th>
<th>$\text{m}/m_{\text{proton}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>e$^-$</td>
<td>-e</td>
<td>0.511</td>
<td>0.0055</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>$\nu_e$</td>
<td>0</td>
<td>$\sim 0$</td>
<td></td>
</tr>
<tr>
<td>mu-minus</td>
<td>$\mu$</td>
<td>-e</td>
<td>105.66</td>
<td>0.1126</td>
</tr>
<tr>
<td>mu-neutrino</td>
<td>$\nu_\mu$</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>tau-minus</td>
<td>$\tau$</td>
<td>-e</td>
<td>1777</td>
<td>1.894</td>
</tr>
<tr>
<td>tau-neutrino</td>
<td>$\nu_\tau$</td>
<td>0</td>
<td>$\sim 0$</td>
<td></td>
</tr>
</tbody>
</table>
## anti-leptons - charge and mass

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge</th>
<th>mass $\text{MeV/c}^2$</th>
<th>mass $\text{m}/m_{\text{proton}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-plus or positron</td>
<td>$e^+$</td>
<td>$+e$</td>
<td>0.511</td>
<td>0.0055</td>
</tr>
<tr>
<td>electron antineutrino</td>
<td>$\bar{\nu}_e$</td>
<td>0</td>
<td>~ 0</td>
<td></td>
</tr>
<tr>
<td>mu-plus</td>
<td>$\mu^+$</td>
<td>$+e$</td>
<td>105.66</td>
<td>0.1126</td>
</tr>
<tr>
<td>mu antineutrino</td>
<td>$\bar{\nu}_\mu$</td>
<td>0</td>
<td>~ 0</td>
<td></td>
</tr>
<tr>
<td>tau-plus</td>
<td>$\tau^+$</td>
<td>$+e$</td>
<td>1777</td>
<td>1.894</td>
</tr>
<tr>
<td>tau antineutrino</td>
<td>$\bar{\nu}_\tau$</td>
<td>0</td>
<td>~ 0</td>
<td></td>
</tr>
</tbody>
</table>
Classification of particles – particles/anti particles

Origin:- particles of exactly the same mass but opposite charge
Later found to have other quantum numbers with opposite values

Symbol:- either
the electric charge as a superscript eg: $\pi^-$ and $\pi^+$, $e^-$ and $e^+
or
particle $P$ anti-particle $\bar{P}$ (often said as P-bar)

Neutral particles/anti-particles:-
some are the same (Majorana) eg $\pi^0$ and
some are different (Dirac) eg neutron, neutrino
The first anti-particles: positrons, 1932 - Anderson

63 MeV positron upwards emerges with 23 MeV) 3 electrons (bend to left) and 3 positrons (bend to right)
# lepton numbers

<table>
<thead>
<tr>
<th>lepton</th>
<th>lepton number</th>
<th>anti-lepton number</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>$e^-$</td>
<td>$l_e$ $l_\mu$ $l_\tau$</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>$\nu_e$</td>
<td>$1$ $0$ $0$</td>
</tr>
<tr>
<td>mu</td>
<td>$\mu$</td>
<td>$0$ $1$ $0$</td>
</tr>
<tr>
<td>mu-neutrino</td>
<td>$\nu_\mu$</td>
<td>$0$ $1$ $0$</td>
</tr>
<tr>
<td>tau</td>
<td>$\tau$</td>
<td>$0$ $0$ $1$</td>
</tr>
<tr>
<td>tau-neutrino</td>
<td>$\nu_\tau$</td>
<td>$0$ $0$ $1$</td>
</tr>
</tbody>
</table>
Decay $\pi^+ \Rightarrow \mu^+ \Rightarrow e^+$

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

$\pi^+ \Rightarrow \mu^+ + \nu_\mu$

Note lepton numbers are conserved
# quarks – charge and mass

<table>
<thead>
<tr>
<th>name</th>
<th>symbol</th>
<th>charge $e$</th>
<th>mass $\text{MeV}/c^2$</th>
<th>$m/m_{\text{proton}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>down</td>
<td>d</td>
<td>$-1/3$</td>
<td>$\sim 7$</td>
<td></td>
</tr>
<tr>
<td>up</td>
<td>u</td>
<td>$+2/3$</td>
<td>$\sim 3$</td>
<td></td>
</tr>
<tr>
<td>strange</td>
<td>s</td>
<td>$-1/3$</td>
<td>120</td>
<td>0.1</td>
</tr>
<tr>
<td>charm</td>
<td>c</td>
<td>$+2/3$</td>
<td>1200</td>
<td>1.3</td>
</tr>
<tr>
<td>bottom</td>
<td>b</td>
<td>$-1/3$</td>
<td>4300</td>
<td>4.8</td>
</tr>
<tr>
<td>top</td>
<td>t</td>
<td>$+2/3$</td>
<td>174000</td>
<td>187</td>
</tr>
</tbody>
</table>
Quark picture 1983

according to

Frank Close
“Cosmic Onion”
Heinemann Educational Books
1983

Top-quark found 1995
## Anti-quark - charge and mass

<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>
</tr>
</thead>
<tbody>
<tr>
<td>anti-down</td>
<td>$\bar{d}$</td>
<td>-1/3</td>
<td>~ 7</td>
<td></td>
</tr>
<tr>
<td>anti-up</td>
<td>$\bar{u}$</td>
<td>+2/3</td>
<td>~ 3</td>
<td></td>
</tr>
<tr>
<td>anti-strange</td>
<td>$\bar{s}$</td>
<td>-1/3</td>
<td>120</td>
<td>0.1</td>
</tr>
<tr>
<td>anti-charm</td>
<td>$\bar{c}$</td>
<td>+2/3</td>
<td>1200</td>
<td>1.3</td>
</tr>
<tr>
<td>anti-bottom</td>
<td>$\bar{b}$</td>
<td>-1/3</td>
<td>4300</td>
<td>4.8</td>
</tr>
<tr>
<td>anti-top</td>
<td>$\bar{t}$</td>
<td>+2/3</td>
<td>174000</td>
<td>187</td>
</tr>
</tbody>
</table>
### quarks – flavour numbers

<table>
<thead>
<tr>
<th>quark</th>
<th>q\textsubscript{d}</th>
<th>q\textsubscript{u}</th>
<th>q\textsubscript{s}</th>
<th>q\textsubscript{c}</th>
<th>q\textsubscript{b}</th>
<th>q\textsubscript{t}</th>
<th>q\textsubscript{d}</th>
<th>q\textsubscript{u}</th>
<th>q\textsubscript{s}</th>
<th>q\textsubscript{c}</th>
<th>q\textsubscript{b}</th>
<th>q\textsubscript{t}</th>
</tr>
</thead>
<tbody>
<tr>
<td>down</td>
<td>d</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</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>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</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>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</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>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</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>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</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>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>
leptons and quarks - masses

Generations 1 2 3
# Fundamental forces

<table>
<thead>
<tr>
<th>force</th>
<th>exchange boson</th>
<th>&quot;charge&quot;</th>
<th>range</th>
<th>mass m/m_p</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>one</td>
</tr>
<tr>
<td>electro-magnetic</td>
<td>photon</td>
<td>electric</td>
<td>infinite</td>
<td>zero</td>
<td>one</td>
</tr>
<tr>
<td>weak</td>
<td>$W^+$</td>
<td>weak</td>
<td>1 am</td>
<td>85.7</td>
<td>three</td>
</tr>
<tr>
<td></td>
<td>$W^-$</td>
<td></td>
<td></td>
<td>85.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z^0$</td>
<td></td>
<td></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>eight</td>
</tr>
</tbody>
</table>
## forces acting between particles

<table>
<thead>
<tr>
<th></th>
<th>gravity</th>
<th>weak</th>
<th>electro-magnetic</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>
Conservation laws - 1

The following quantities are conserved in all interactions:

- the total before must be the same as the total afterwards

- Charge
- Energy
- Linear momentum
- Angular momentum
### Conservation laws - 2

The following quantities are conserved in interactions as indicated:
- S strong; E electromagnetic; W weak

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>E</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryon number</td>
<td>y</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>Lepton flavour numbers</td>
<td>y</td>
<td>y</td>
<td>y</td>
</tr>
<tr>
<td>Quark flavour numbers</td>
<td>y</td>
<td>y</td>
<td>n</td>
</tr>
<tr>
<td>Colour</td>
<td>y</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Classification of particles: photons, leptons, mesons and baryons

- Originally described mass.
  - Photons no mass
  - Leptons light $0.5 \text{ MeV/c}^2$
  - Mesons medium $100-500 \text{ MeV/c}^2$
  - Baryons heavy $> 900 \text{ MeV/c}^2$

Still useful:-
turns out that this also describes structure and quark content.
Classification of particles – baryons and mesons and hadrons

- **Hadrons**
  - **Baryons**
    - Contain quarks
    - Three quarks
    - Or
    - Three anti-quarks (anti baryons)
  - **Mesons**
    - A quark and an anti-quark
Classification of particles – baryons and mesons and hadrons

Baryons

- three quarks
- or
- three anti-quarks (anti baryons)

Mesons

- a quark and an anti-quark

Hadrons

- valence quarks
- gluons and sea quarks
Baryons:- proton and the neutron

the proton \( uud \)
+ sea quarks and gluons

the neutron \( udd \)
+ sea quarks and gluons
mesons: - the pion family

\[ \pi^+ \]
\[ \pi^0 \]
\[ \pi^- \]

u:d-bar
u:u-bar
d:d-bar
u-bar:d
“Colour - 1”

Chromodynamics :- theory of the strong interaction, colour plays the same role as charge in electrodynamics.

Need three colours, but hadrons have to be colourless
Use red, green and blue (parallel to TV and photo and print)
Anti-colours = white – colour ; cyan, magenta and yellow

Gluons have a colour and an anti colour
“Colour - 2”

Quarks have colour, anti-quarks have anti-colour

Baryons: one (valence) quark of each colour (anti-baryons have three anti-colours)

Mesons: quark(colour)+anti-quark(anti-colour)

Leptons, photons, W’s, Z\(^0\) do not have a colour
Classification of particles - generations

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>First generation:</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$u$</td>
</tr>
<tr>
<td>$e$</td>
<td>$d$</td>
</tr>
<tr>
<td>Second generation:</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>$c$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$s$</td>
</tr>
<tr>
<td>Third generation:</td>
<td></td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>$t$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$b$</td>
</tr>
</tbody>
</table>

The upper member of each doublet is more positive
Classification of particles
fermions and bosons

Fermions obey the Pauli exclusion principle:-
“two particles with the same quantum numbers cannot occupy the same quantum state”

Bosons don’t:-
“any number of identical bosons can occupy the same quantum state”

Another way of saying this is:-
“Fermions follow Fermi/Dirac statistics, bosons follow Bose/Einstein statistics”
Classification of particles
fermions and bosons

Fermions:- leptons, quarks,
neutron, proton and other baryons

Bosons:- photons, gluons, W’s and Z\(_0\)
mesons

A nucleus can be either depending on its spin.
Classification of particles
fermions and bosons

Fermions have half integral spin: -1/2, 3/2, 5/2, 7/2 …

Bosons have integral spin: -0, 1, 2, 3 …

Spin magnitude and its orientation are quantum numbers, as are the allowed projections onto a preferred direction.

Eg spin 3/2: -3/2, -1/2, +1/2, +3/2

spin 2: -2, -1, 0, +1, +2

Are two different quantum states

+1/2 -1/2

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Various decay modes of nucleus

**Alpha decay**

\[ X(A, Z) \Rightarrow Y(A-4, Z-2) + \alpha \]

**Beta minus decay**

\[ X(A, Z) \Rightarrow Y(A, Z+1) + e^- + \nu \]

**Beta plus decay**

\[ X(A, Z) \Rightarrow Y(A, Z-1) + e^+ + \nu \]
Standard Model and Nuclear Physics

The nucleons remain as individual particles in the quantum well formed by the other nucleons in the nucleus.

Alpha, gamma decays, fission and fusion are reactions at the nuclear level. They are the result of nucleon to nucleon interactions via the “strong nuclear force”.

Beta decay is an interaction at the quark level.
The "strong nuclear force" is an exchange force mediated by (mostly) pi-mesons: $\pi^+ (u \bar{d})$, $\pi^- (\bar{u} d)$, $\pi^0$ (mix of $u\bar{u}$ and $d\bar{d}$).

The "strong nuclear force" is like the inter-molecular Van der Waals force, which is the result of the adding the electromagnetic forces, from the component electrons and nuclei, outside the neutral molecule.
Beta decay – nuclear and nucleon level

Nuclear level

Beta minus decay

\[ N^*(A, Z) \Rightarrow N(A, Z+1) + e^- + \bar{\nu}_e \]

Beta plus decay

\[ N^*(A, Z) \Rightarrow N(A, Z-1) + e^+ + \nu_e \]

Nucleon level – within a nucleus

\[ n \Rightarrow p + e^- + \bar{\nu}_e \quad \text{also for free neutron} \]

\[ p \Rightarrow n + e^+ + \nu_e \]
Beta decay – quark level

\[\mathbf{u} \Rightarrow \mathbf{d} + W^+ \rightarrow \beta^+ + \nu_e\]