Outline

- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Classification of particles
  - Fermions and bosons
  - Leptons, hadrons, quarks
  - Mesons, baryons
- Quark Model
  - Meson and baryon multiplets
  - Isospin, strangeness, c, b, t quarks
- Particle Interactions
  - Virtual particles and range of forces
  - Strong and weak decays, conservation rules
  - Parity, charge conjugation, CP
  - Weak decays of quarks
  - Colour charge, QCD, gluons
  - Charmonium and upsilon systems
- Electroweak Interactions
  - Charged and neutral currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future – introduction to accelerator physics

Today

- Lecture 7 (4 slides/page) - meson and baryon multiplets
  - Cottingham, pp. 30-35, 37-41 (recommend).
  - Perkins (3rd edition), pp.146-152 (recommend).
  - Williams, pp.109 - 200.
  - V.E. Barnes et al. (1964), "Observation of a Hyperon with Strangeness Number Three", Phys. Rev.

Today

- Lecture 6 (4 slides/page) - static quark model
  - Particle discoveries before quark model proposed (1964)
  - Particle discoveries after 1964
  - Early proton synchrotrons
  - Discovery of the pion - Nature 159, 186–190 & 160, 453–456 (1947)
  - Discovery of strange particles - Nature 160, 855-857 (1947)
  - Williams Ch. 10.3; Perkins (3rd Ed.), pp. 146-150.

u, d meson groupings

$q\bar{q}$	S=0	S=1
$u\bar{d}$	$\pi^+(140)$	$\rho^+(770)$
$\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d})$	$\pi^0(135)$	$\rho^0(770)$
$\bar{u}d$	$\pi^-(140)$	$\rho^-(770)$
$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$	$\eta(548)$	$\omega(782)$

- Meson triplet and singlet with u, d flavours
- (xxx) are masses in MeV - conventional

Strangeness: light meson nonets

$q\bar{q}$	$^1S_0$, J=0	$^3S_0$, J=1
$u\bar{d}$	$\pi^+(140)$	$\rho^+(770)$
$\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d})$	$\pi^0(135)$	$\rho^0(770)$
$\bar{u}d$	$\pi^-(140)$	$\rho^-(770)$
$u\bar{s}$	$K^+(494)$	$K^{*+}(892)$
$d\bar{s}$	$K^0(498)$	$K^{*0}(896)$
$\bar{u}s$	$K^-(494)$	$K^{*-}(892)$
$\bar{d}s$	$\bar{K}^0(498)$	$\bar{K}^{*0}(896)$
$\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})$	$\eta(548)$	$\omega(782)$
$s\bar{s}$	$\eta'(958)$	$\phi(1020)$

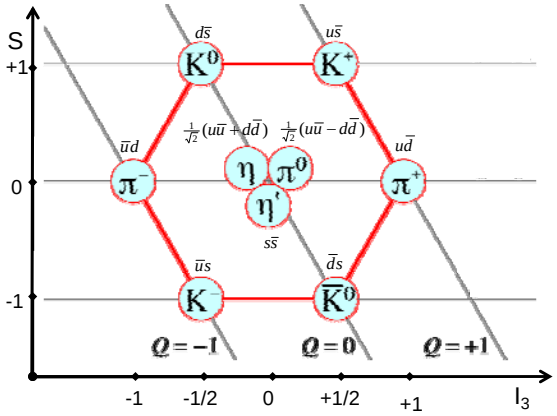
- Extend meson combinations by introduction of s quark, gives "nonets"
- Note η, η' are actually mixed states from $u\bar{u}, d\bar{d}, s\bar{s}$
- ω and ϕ also slight admixtures
- (xxx) are masses in MeV - conventional

Quantum Numbers of Quarks

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

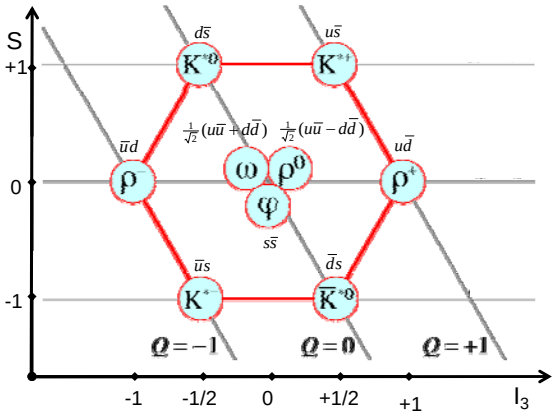
- These quantum numbers are additive
- Flavour is conserved by strong and e.m. interactions.
- E.m. charge is given by Gell-Mann-Nishijima formula $Q = I_3 + \frac{1}{2}(S+C+T+B)$
- Use B to denote baryon number (1/3 for quarks, -1/3 for anti-quarks)
- Flavour is not conserved by weak interactions mediated by W^+, W^- ("charged current").

$^1S_0$ Meson Nonet



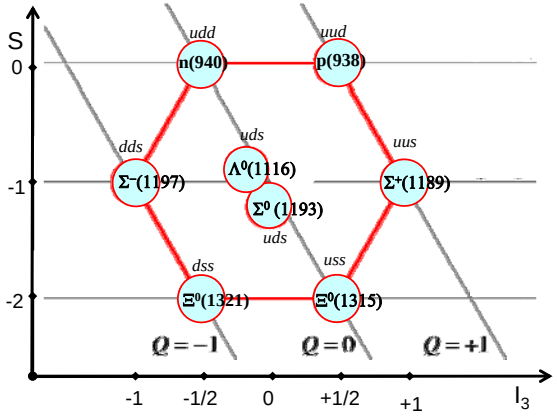
[adapted from http://en.wikipedia.org/wiki/File:Meson_nonet_-_spin_0.svg]

$^3S_1$ Meson Nonet



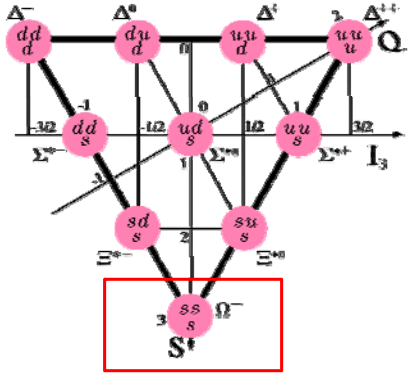
[adapted from http://en.wikipedia.org/wiki/File:Meson_nonet_-_spin_1.svg]

J=1/2 Baryon Octet



[adapted from http://en.wikipedia.org/wiki/File:Meson_nonet_-_spin_1.svg]

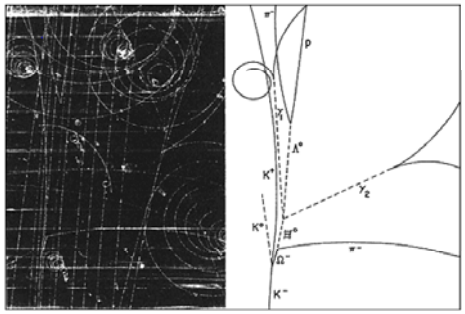
J=3/2 Baryon Decuplet



- Ω^- not observed initially but predicted from pattern in quark model.
- Existence of the S=-3 (sss) baryon at at mass ~1680 MeV/c^2
- Identified based on a single event in bubble chamber (1964)
  - 3 very characteristic weak decays
  - 1st successful prediction of quark model!

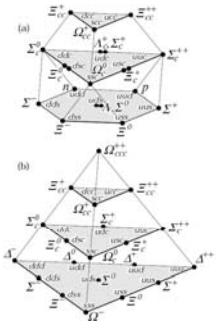
[from http://en.wikipedia.org/wiki/File:Baryon-decuplet-small.svg]

Discovery of Ω^- at BNL (1964)



- V. E. Barnes *et al.* (1964), "Observation of a Hyperon with Strangeness Number Three", Phys. Rev. Lett. 12, 204-206 (1964)

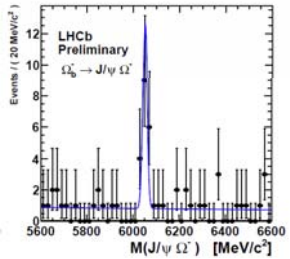
4 flavour baryon multiplets



- Addition of c quark…
  - Extra dimension required to visualise
- Some c baryons discovered, so far none with C=+2
- Inclusion of b quark, very hard to visualise in this manner

Example of SU(4) baryon multiplets with four flavours
[http://hepdata.cedar.ac.uk/lbl/2011/reviews/rpp2011-rev-quark-model.pdf]
K. Nakamura *et al.*, JPG **37**, 075021 (2010)

Recent progress on baryons…



LHCb-CONF-2011-060 ; CERN-LHCb-CONF-2011-060, "Measurement of the masses of the Ξ_b^- and Ω_b^-"

https://cdsweb.cern.ch/record/1395530?ln=en

Preliminary result, appears to help clarify discrepancies between CDF and D0.

Table 3: LHCb mass measurements, compared to the PDG averages [4] and the results of the CDF [2] and DØ [1] experiments. The quoted errors include statistical and systematic uncertainties. All values are in MeV/c^2.

	$M(\Xi_b^-)$	$M(\Omega_b^-)$
DØ	5774 ± 19	6165 ± 16
CDF	5790.9 ± 2.7	6054.4 ± 6.9
PDG	5790.5 ± 2.7	6071 ± 40
LHCb	5796.5 ± 1.7	6050.3 ± 5.0

Mesons Stable Against Strong Decay

Particle (Anti-particle)	J	I_3	S	C	B	Mass (MeV/c^2)	Mean Life (s)
π^+ (π^-)	0	+1(−1)	0	0	0	139.6	2.60×10^{-8}
π°	0	0	0	0	0	135.0	8.4×10^{-17}
K^+ (K^-)	0	+½ (−½)	+1(−1)	0	0	493.7	1.24×10^{-8}
K° ($\overline{K}^\circ$)	0	−½ (+½)	+1(−1)	0	0	497.6	$\{9.0 \times 10^{-11}$ $\{5.1 \times 10^{-8}$
η°	0	0	0	0	0	547.9	5.1×10^{-19}
D^+ (D^-)	0	+½ (−½)	0	+1(−1)	0	1870	1.0×10^{-12}
D° ($\overline{D}^\circ$)	0	−½ (+½)	0	+1(−1)	0	1865	4.1×10^{-13}
D^+_s (D^-_s)	0	0	+1(−1)	+1(−1)	0	1968	5.0×10^{-13}
B^+ (B^-)	0	+½ (−½)	0	0	+1(−1)	5279	1.6×10^{-12}
B° ($\overline{B}^\circ$)	0	−½ (+½)	0	0	+1(−1)	5280	1.5×10^{-12}
B°_s ($\overline{B}^\circ_s$)	0	0	−1(+1)	0	+1(−1)	5366	1.5×10^{-12}
B^+_c (B^-_c)	0	0	0	+1(−1)	+1(−1)	6276	4.6×10^{-13}

Baryons Stable Against Strong Decay

Particle	J	I_3	S	C	B	Mass (MeV/c^2)	Mean Life (s)
p	½	½	0	0	0	938.3	$> 2.1 \times 10^{29}$ years
n	½	–½	0	0	0	939.6	886
Λ	½	0	–1	0	0	1116	2.6×10^{-10}
Σ^+	½	+1	–1	0	0	1189	8.0×10^{-11}
Σ°	½	0	–1	0	0	1193	7.4×10^{-20}
Σ^-	½	–1	–1	0	0	1197	1.5×10^{-10}
Ξ°	½	+½	–2	0	0	1315	2.9×10^{-10}
Ξ^-	½	–½	–2	0	0	1322	1.6×10^{-10}
Ω^-	½	0	–3	0	0	1672	8.2×10^{-11}
Λ_c^+	½	0	0	1	0	2286	2.0×10^{-13}
Ξ_c^+	½	+½	–1	1	0	2468	4.4×10^{-13}
Ξ_c°	½	– ½	–1	1	0	2471	1.1×10^{-13}
Ω_c°	½	0	–2	1	0	2698	6.9×10^{-14}
Λ_b°	½	0	0	0	–1	5620	1.4×10^{-12}