

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

Please see web page for specific references to textbooks and brief reviews from PDG.

u, d meson groupings

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

■ Meson triplet and singlet with u, d flavours

■ (xxx) are masses in MeV - conventional

$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	$\eta(548)$	$\omega(782)$
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Strangeness: light meson nonets

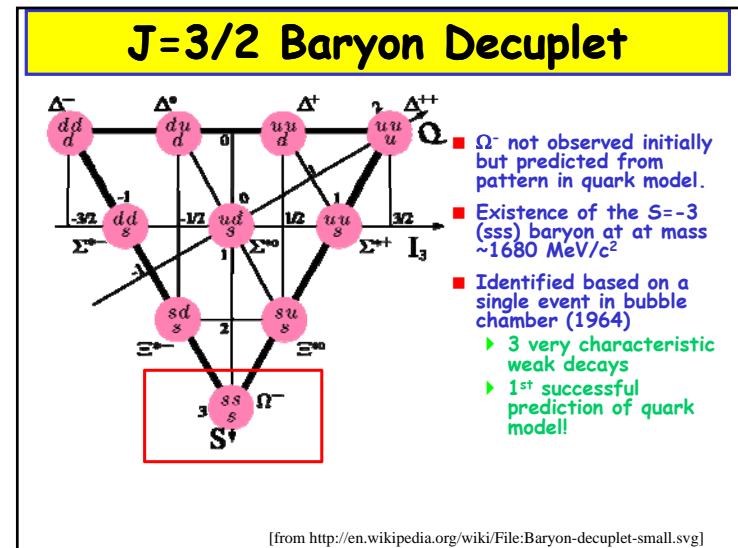
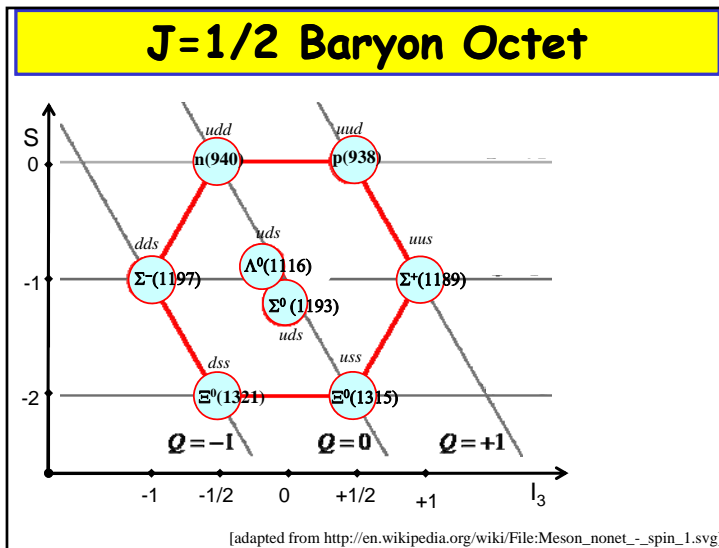
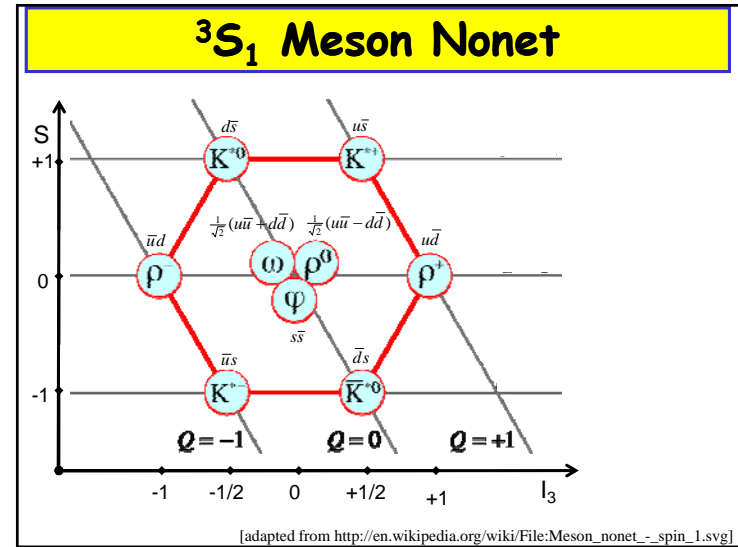
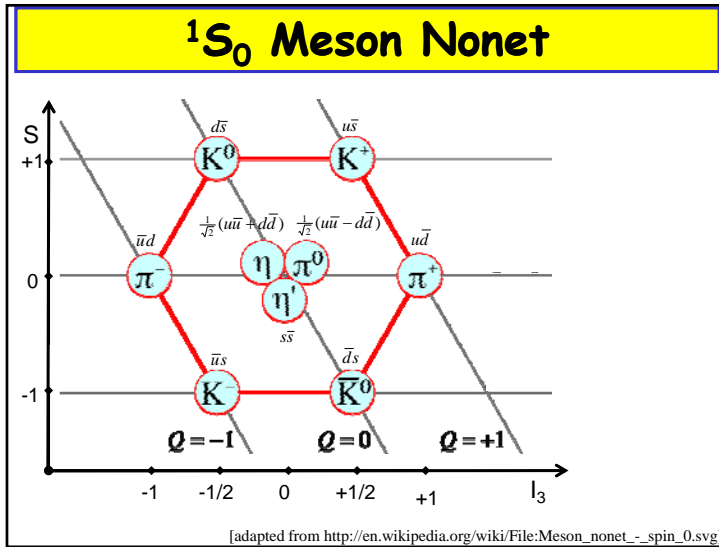
$q\bar{q}$	$^1S_0, J=0$	$^3S_0, J=1$
$u\bar{d}$	$\pi^+(140)$	$\rho^+(770)$
$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$\pi^0(135)$	$\rho^0(770)$
$\bar{u}d$	$\pi^-(140)$	$\rho^-(770)$
$u\bar{s}$	$K^+(494)$	$K^{*+}(892)$
$d\bar{s}$	$K^0(498)$	$K^{*0}(896)$
$\bar{u}s$	$K^-(494)$	$K^{*-}(892)$
$\bar{d}s$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

- 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

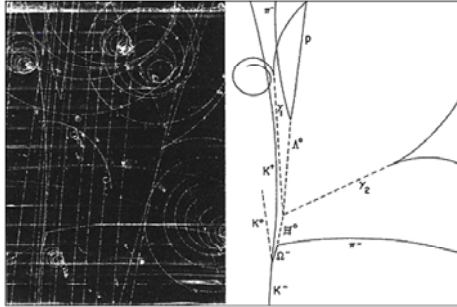
Quantum Numbers of Quarks

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 $Q = I_3 + \frac{1}{6}(S+C+T+B+3)$
- 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").

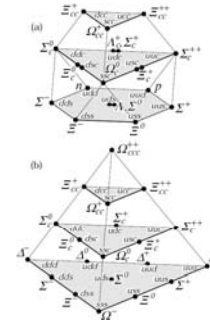


Discovery of Ω^- at BNL (1964)



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

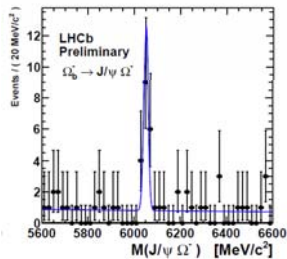
4 flavour baryon multiplets



- 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 D0 [1] experiments. The quoted errors include statistical and systematic uncertainties. All values are in MeV/c^2 .

	$M(\Xi_b^-)$	$M(\Omega_b^-)$
D0	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	0	135.0	8.4×10^{-17}
K^+ (K^-)	0	+(-)	+1(-1)	0	0	493.7	1.24×10^{-8}
K^0 (\bar{K}^0)	0	-(+)	+1(-1)	0	0	497.6	$\{9.0 \times 10^{-11}$ $\{5.1 \times 10^{-8}$
η^0	0	0	0	0	0	547.9	5.1×10^{-19}
D^+ (D^-)	0	+(-)	0	+1(-1)	0	1870	1.0×10^{-12}
D^0 (\bar{D}^0)	0	-(+)	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	+(-)	0	0	+1(-1)	5279	1.6×10^{-12}
B^0 (\bar{B}^0)	0	-(+)	0	0	+1(-1)	5280	1.5×10^{-12}
B_s^0 (\bar{B}_s^0)	0	0	(+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	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	938.3	$> 2.1 \times 10^{29}$ years
n	$\frac{1}{2}$	$-\frac{1}{2}$	0	0	0	939.6	886
Λ	$\frac{1}{2}$	0	-1	0	0	1116	2.6×10^{-10}
Σ^+	$\frac{1}{2}$	+1	-1	0	0	1189	8.0×10^{-11}
Σ^0	$\frac{1}{2}$	0	-1	0	0	1193	7.4×10^{-20}
Σ^-	$\frac{1}{2}$	-1	-1	0	0	1197	1.5×10^{-10}
Ξ^0	$\frac{1}{2}$	$+\frac{1}{2}$	-2	0	0	1315	2.9×10^{-10}
Ξ^-	$\frac{1}{2}$	$+\frac{1}{2}$	-2	0	0	1322	1.6×10^{-10}
Ω^-	$\frac{1}{2}$	0	-3	0	0	1672	8.2×10^{-11}
Λ_c^+	$\frac{1}{2}$	0	0	1	0	2286	2.0×10^{-13}
Ξ_c^+	$\frac{1}{2}$	$+\frac{1}{2}$	-1	1	0	2468	4.4×10^{-13}
Ξ_c^0	$\frac{1}{2}$	$-\frac{1}{2}$	-1	1	0	2471	1.1×10^{-13}
Ω_c^0	$\frac{1}{2}$	0	-2	1	0	2698	6.9×10^{-14}
Λ_b^0	$\frac{1}{2}$	0	0	0	-1	5620	1.4×10^{-12}