

Class 5 - The Quark Model

- Quarks
- Mesons - Quark/Antiquark Combinations
- Baryons - Three Quark Combinations
- Antiparticles
- Spin Considerations
- Color
- Experimental Evidence for Quarks

Birth of the Quark Model

- In 1964, Murray Gell-Mann and George Zweig independently developed a theory that would explain all the hadrons
- Model based on 3 constituent particles, all with spin of $\frac{1}{2}$ and baryon number of $\frac{1}{3}$
- Gell-Mann named them quarks
- Quarks come in three flavors

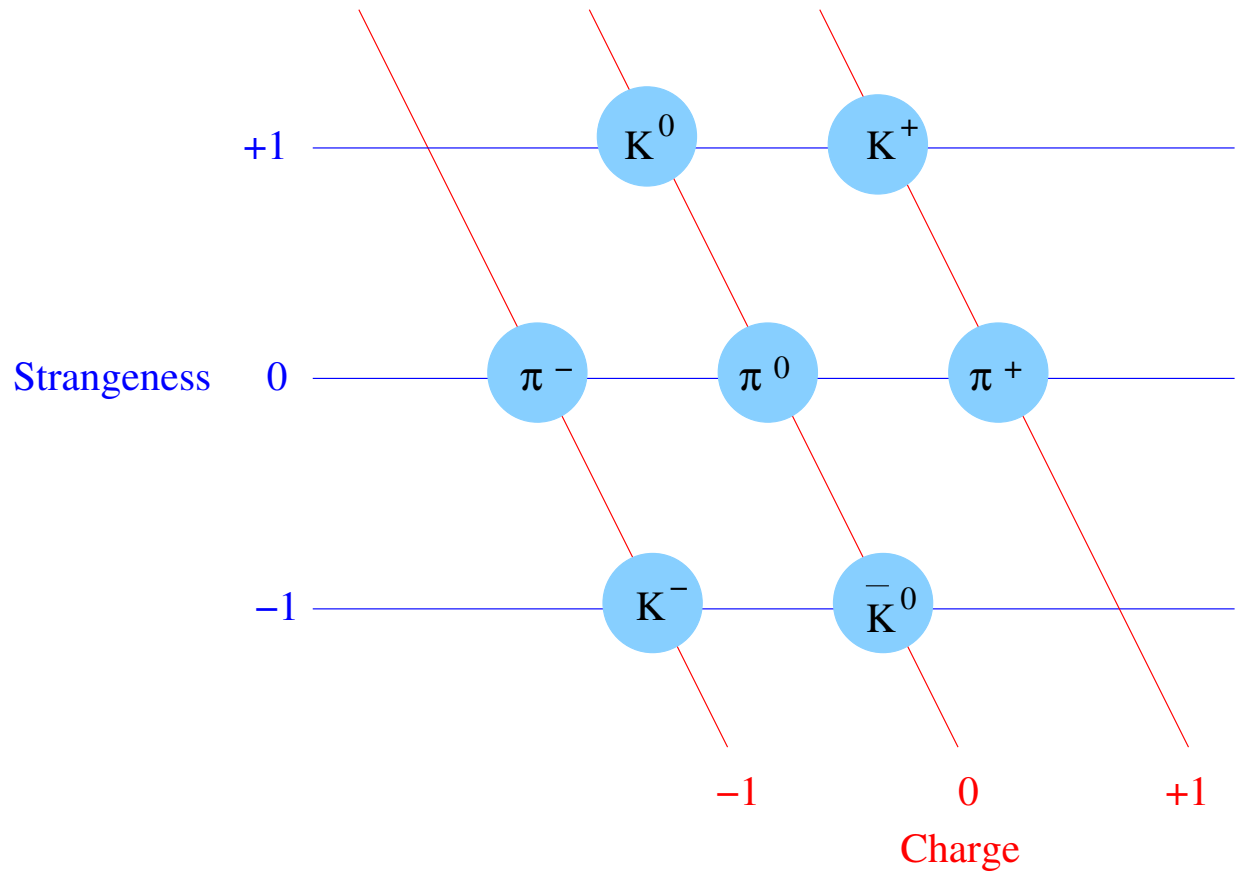
Name	Symbol	Charge	Strangeness
up	u	$+2/3$	0
down	d	$-1/3$	0
strange	s	$-1/3$	-1
antiup	\bar{u}	$-2/3$	0
antidown	\bar{d}	$+1/3$	0
antistrange	\bar{s}	$+1/3$	+1

Mesons

- Mesons are quark/antiquark combinations

Combination	Charge	Strangeness	Meson
$u\bar{u}$	0	0	$\pi^0, \eta^0, \eta^{0'}$
$d\bar{d}$	0	0	$\pi^0, \eta^0, \eta^{0'}$
$\bar{u}d$	-1	0	π^-
$u\bar{d}$	+1	0	π^+
$u\bar{s}$	+1	+1	K^+
$\bar{u}s$	-1	-1	K^-
$d\bar{s}$	0	+1	K^0
$\bar{d}s$	0	-1	\bar{K}^0
$s\bar{s}$	0	0	$\eta^{0'}$

Meson Diagram

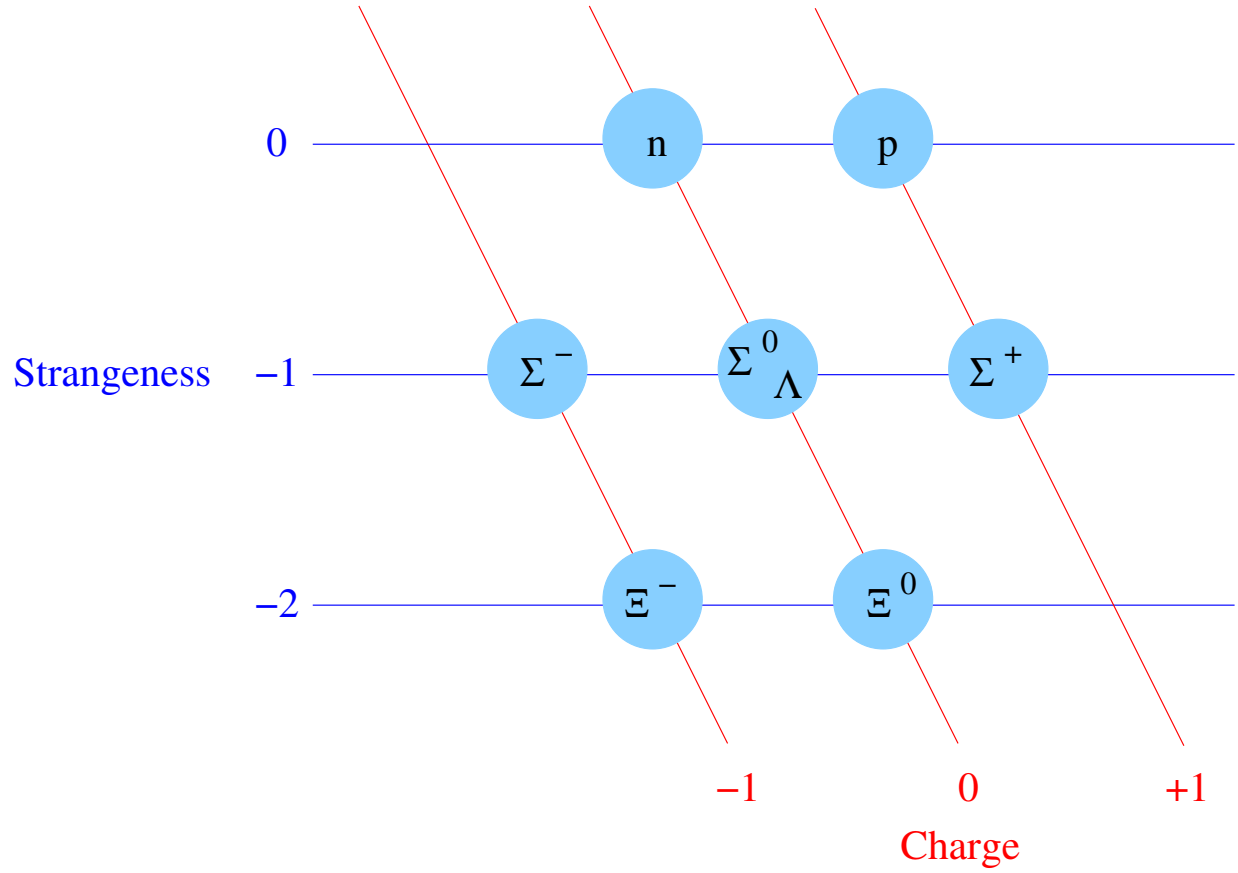


Baryons

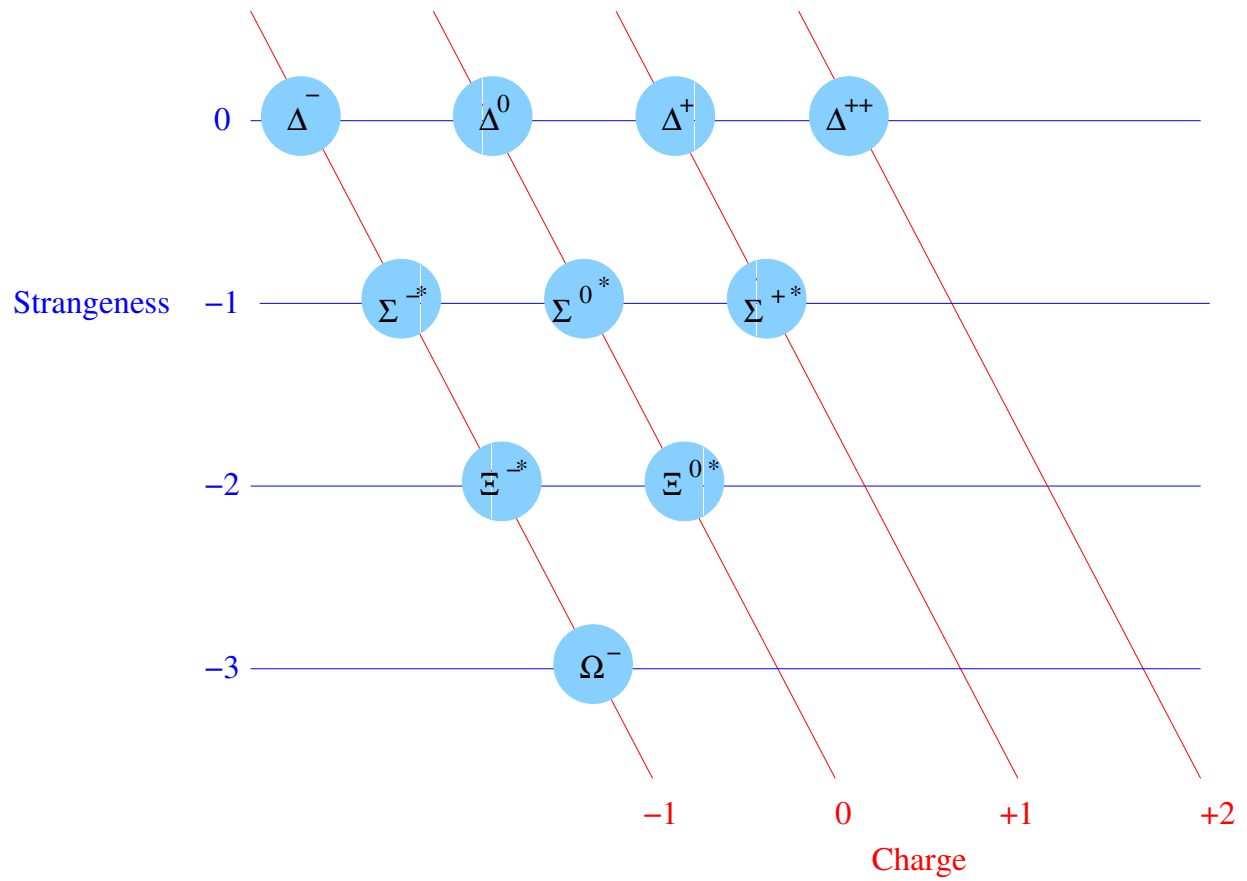
- Baryons are three quark combinations

Combination	Charge	Strangeness	Spin-1/2 Baryon	Spin-3/2 Baryon
uud	1	0	p	Δ^+
udd	0	0	n	Δ^0
uuu	2	0		Δ^{++}
ddd	-1	0		Δ^-
uus	1	-1	Σ^+	Σ^{+*}
uds	0	-1	Λ, Σ^0	Σ^{0*}
dds	-1	-1	Σ^-	Σ^{-*}
uss	0	-2	Ξ^0	Ξ^{0*}
dss	-1	-2	Ξ^-	Ξ^{-*}
sss	-1	-3		Ω^-

Spin- $\frac{1}{2}$ Baryons



Spin-3/2 Baryons



Eightfold Way

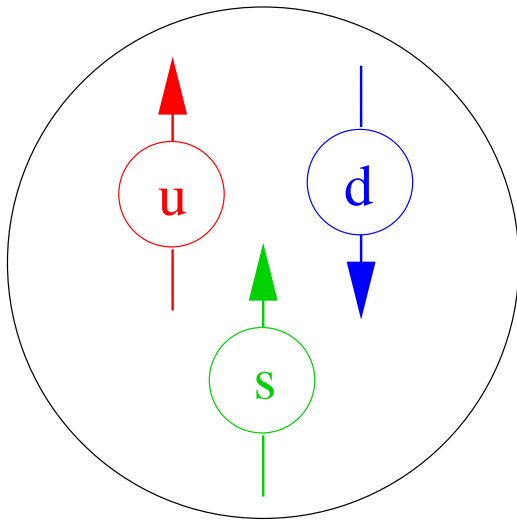
- The patterns displayed by the strangeness versus charge diagrams for the mesons, spin- $\frac{1}{2}$ baryons, and spin- $\frac{3}{2}$ baryons were part of a theory called the Eightfold Way developed in 1961
- This theory predicted the existence of the Ω^-
- The Ω^- was discovered at Brookhaven National Lab in 1963

Antiparticles

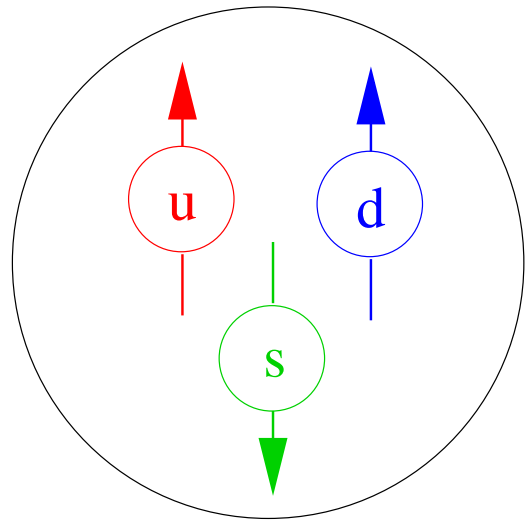
- An antiparticle contains the antiquarks of the quarks in the corresponding particle
- The neutron and the antineutron
 - $n = udd$
 - $\bar{n} = \bar{u}\bar{d}\bar{d}$
- The positive pion and the negative pion
 - $\pi^+ = u\bar{d}$
 - $\pi^- = \bar{u}d$
- The neutral pion is its own antiparticle
 - $\pi^0 = u\bar{u}$ or $d\bar{d}$
 - $\bar{\pi}^0 = \bar{u}u$ or $\bar{d}d$

Spin Considerations

- The internal spin states of the quarks distinguishes different baryons made up of the same three quarks
- For example, the Λ and Σ^0 both have a quark content of uds



Λ



Σ^0

Color

- Color is another property of quarks
- The different flavors of quarks come in three different colors - red, green, and blue
- Color was originally proposed to allow for the Pauli Exclusion Principle to be obeyed in the case of the Ω^-
- Pauli Exclusion Principle states that spin-1/2 particles that are identical can not exist in the same entity
- The Ω^- is made of three s quarks
- If the Pauli Principle is to be obeyed, the s quarks in the Ω^- must have some property that distinguishes them from each other
- The color theory is called quantum chromodynamics

Experimental Evidence for Quarks

- A free quark has never been detected
- However, there is compelling evidence that quarks exist
- In the 1970s, electron scattering from the proton gave results analogous to Rutherford's experiments
- The distributions of the scattered electrons were consistent with the quark model of the proton
- The experiments were able to show that the proton is composed of three spin-1/2 particles, two with charges of $+2/3$ and one with a charge of $-1/3$
- Later experiments have yielded evidence for the existence of gluons inside protons, supporting the theory that they are the carriers of the strong force

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c ²	Electric charge
g gluon	0	0

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Homework

- Read the rest of TSZ