The Strong Interaction

The simplest model for the strong interaction between hadrons (including nuclei) is

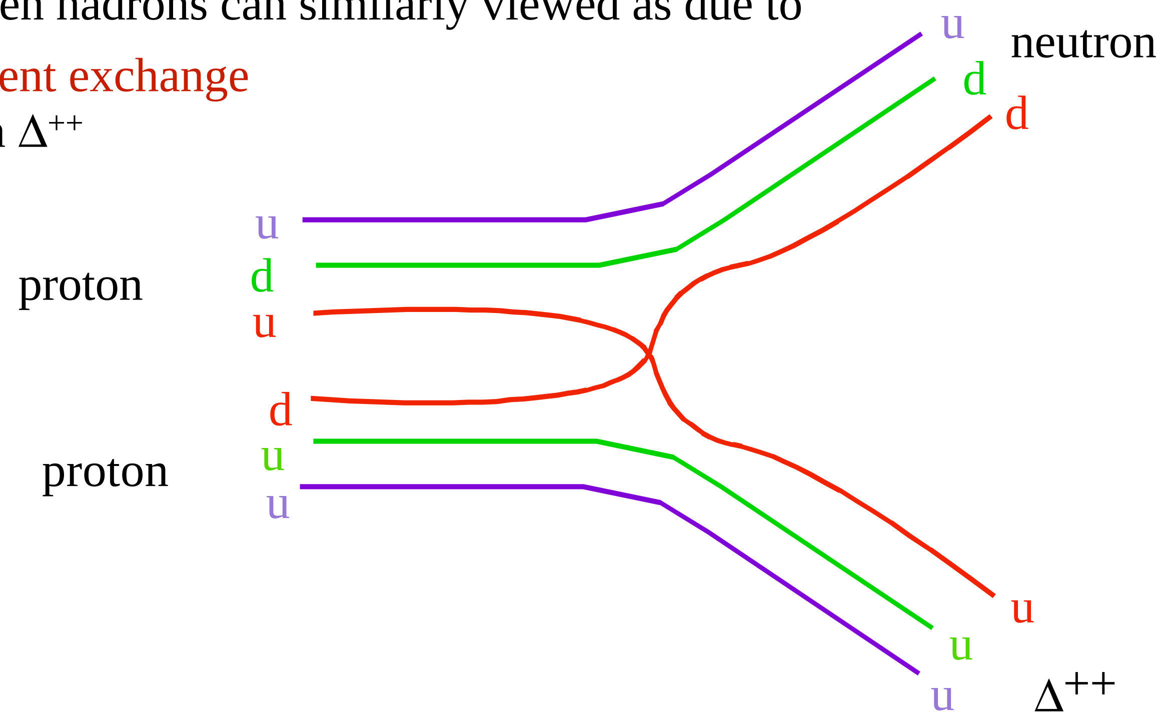
- billiard balls

The forces between real billiard balls are contact forces between neutral atoms. These short range contact forces are due to the fact that neutral atoms are made from electromagnetically charged constituents. (Such forces - e.g. Van der Waals forces, atomic bonds - are general features of composite systems made charged constituents.)

Since hadrons are made of constituent quarks, it is natural to expect that a short range force between hadrons can similarly viewed as due to

- constituent exchange

e.g. p p -> n Δ^{++}

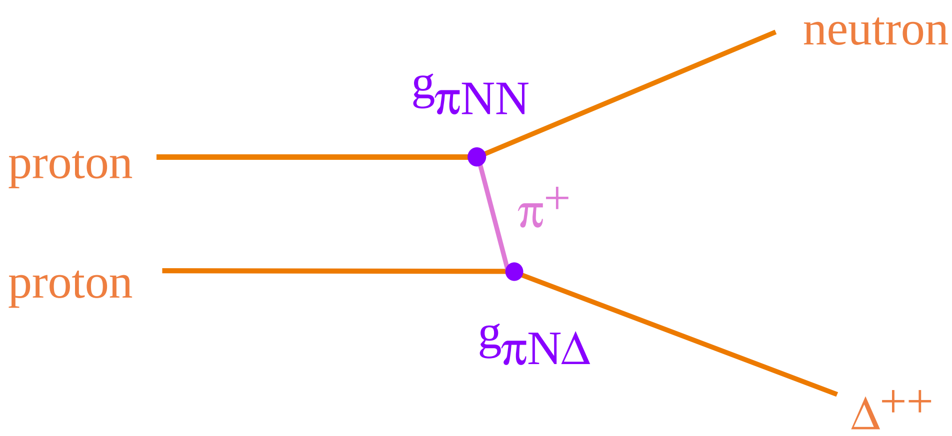


Meson Exchange

When such pairs of quarks are exchanged, the amplitudes are dominated by "poles" due the existence of quark-antiquark resonances, i.e. mesons. The lowest mass resonances dominate the exchanges, so low energy forces can be well described by

- pion exchange

e.g. p p -> n Δ^{++}

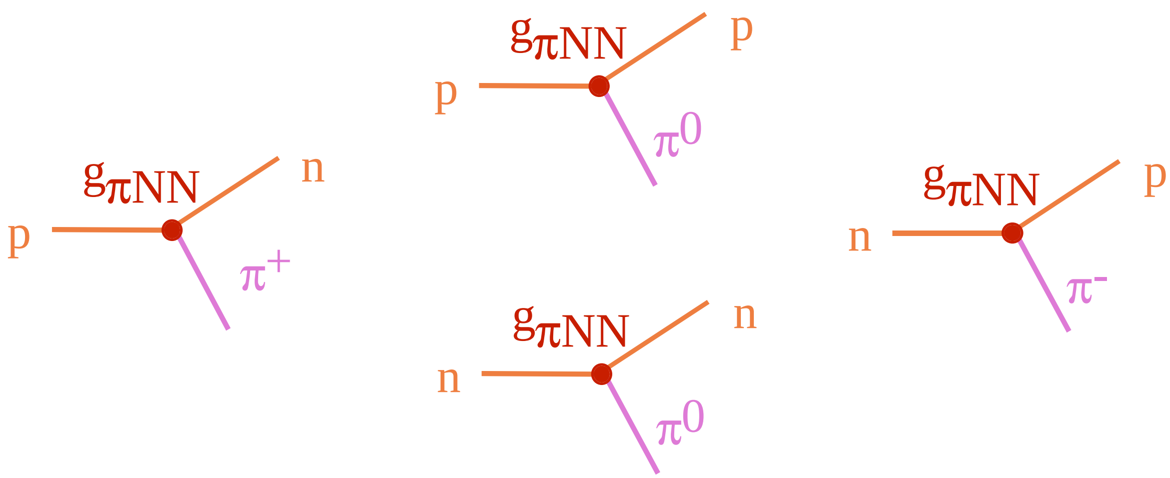


Yukawa predicted the existence of the pion based on the observed strong interaction isospin symmetry between protons and neutrons. (This symmetry is due to the fact that interchanging up and down quarks has only a very small effect on hadron properties.)

Effective SU(2)$_{isospin}$ Gauge Theory

The philosophy behind the isospin theory of the strong interaction was that isospin is a symmetry of the strong interaction, so maybe isospin is the charge of the strong interaction.

e.g. nucleon-nucleon couplings



This is a good effective theory at low energies, but it breaks down at high energies because neither nucleons or pions are point particles.

A more fundamental theory is needed.

Quark Model

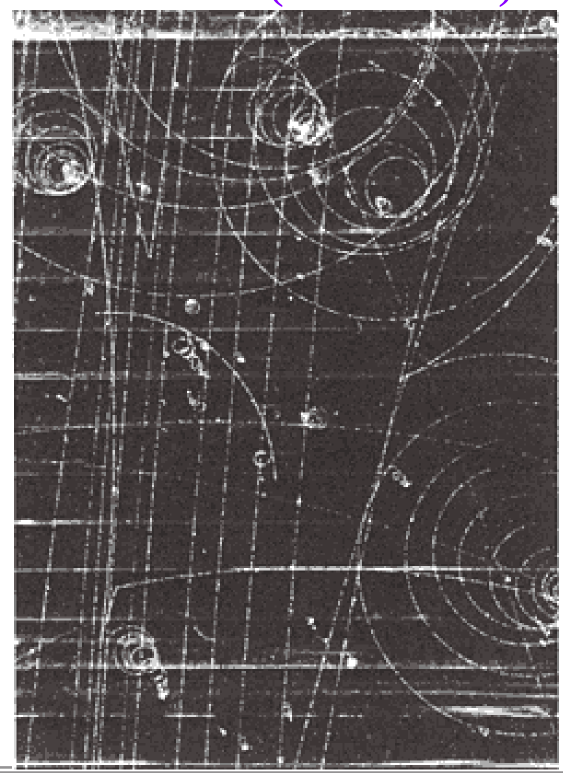
In the 1960's there was a problem with new quark model of hadrons. There are two L=0 ground state baryon multiplets. Considering only baryons containing up, down, and strange quarks they are

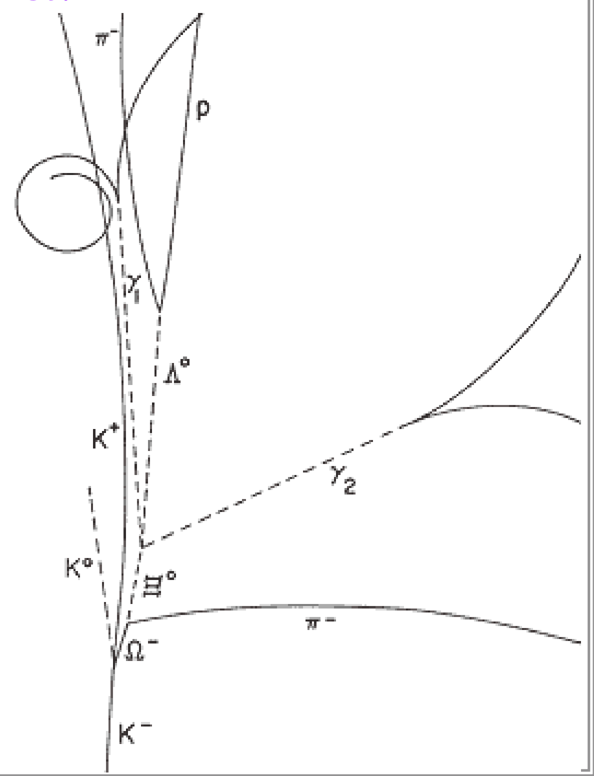
- A $J^P = {}^{1}/_{2}^{-}$ octet: one quark has spin aligned opposite to the other two quarks.
- A $J^P = {}^{3}/_{2}^{-}$ octet: with all quark spins aligned.

The Pauli exclusion principle forbids identical fermions in the same quantum state, so

How can the Δ^{++} (or Δ^{0} or Ω^{-}) exist?

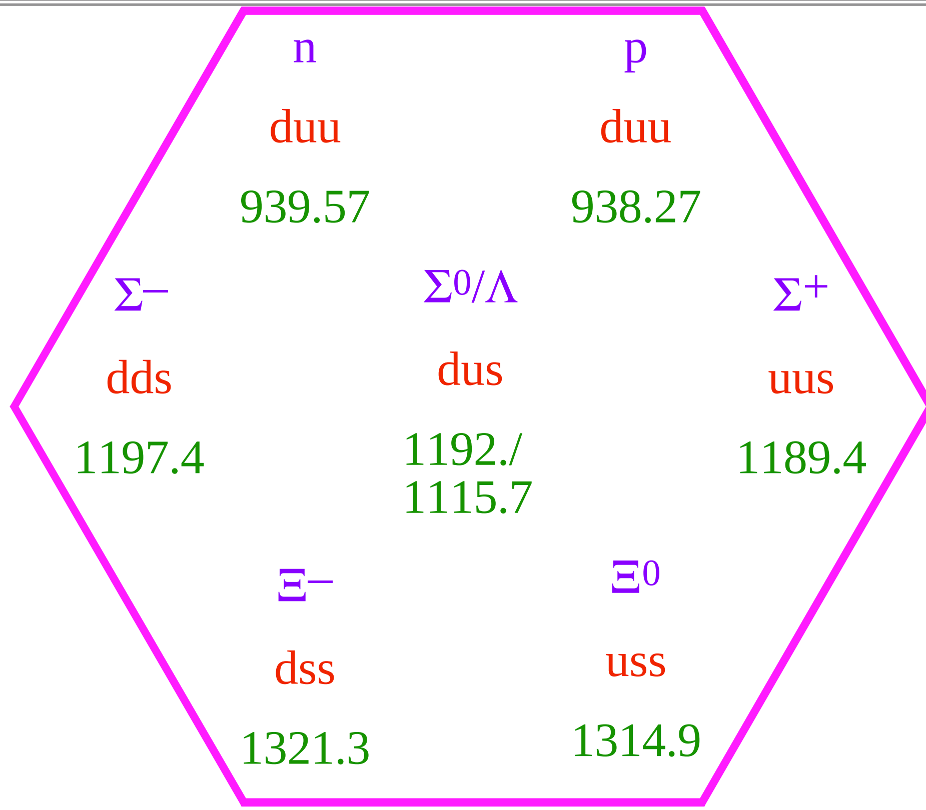
The discovery of the Omega-minus confirmed the power of the quark model, so colour was introduced as a new quantum number associated with quarks. Colour makes it possible for the quark model to obey Fermi-Dirac statistics.





$J^P = {}^1/_2{}^-$ baryon octet

name,
quarks,
mass (MeV)

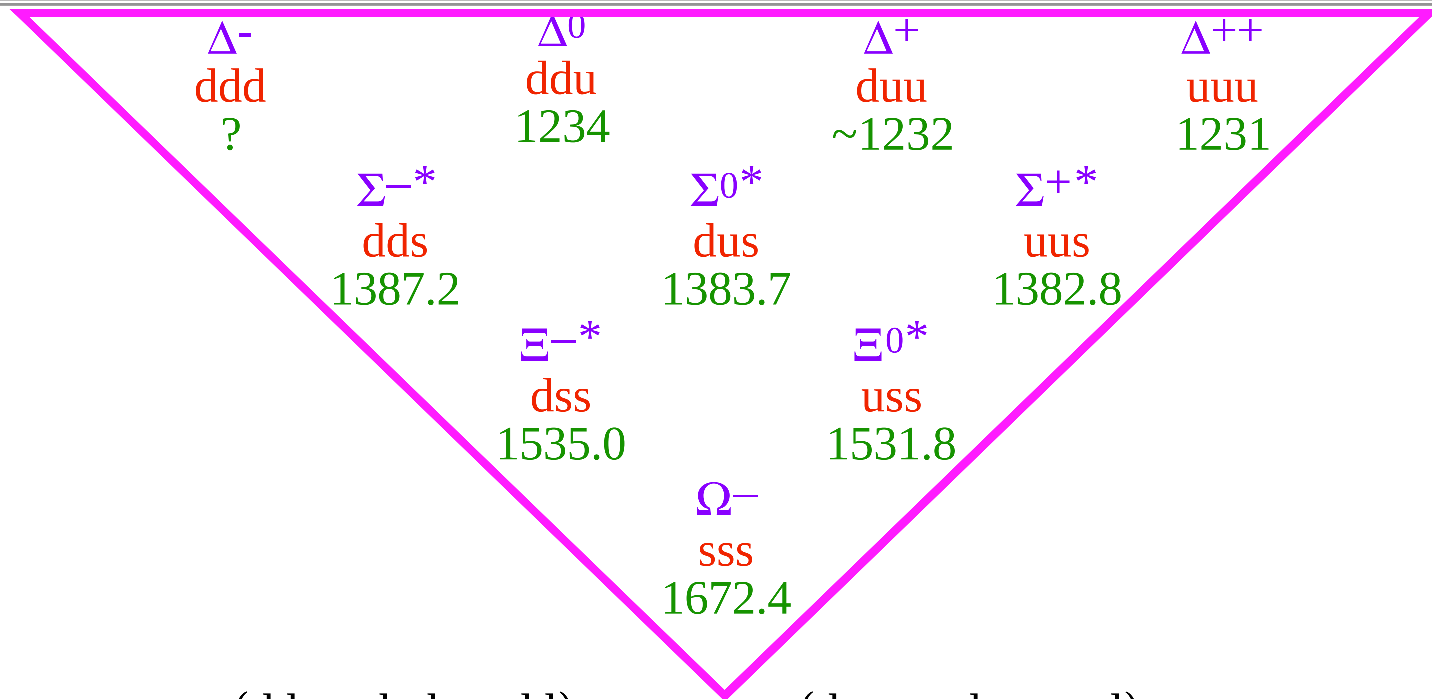


Each member of the octet has simultaneous flavour-spin symmetry, e.g.

neutron: {2 d↑d↑u↓ + 2 u↓d↑d↑ + 2 d↑u↓d↑ - d↓u↑d↑ - d↑d↓u↑ - d↓d↑u↑ - u↑d↓d↑ - d↑u↑d↓ - u↑d↑d↓}/$\sqrt{18}$

proton: {2 u↑u↑d↓ + 2 d↓u↑u↑ + 2 u↑d↓u↑ - u↓d↑u↑ - u↑u↓d↑ - u↓u↑d↑ - d↑u↓u↑ - u↑d↑u↓ - d↑u↑u↓}/$\sqrt{18}$

$J^P = {}^3/_2{}^-$ decuplet



ddd $\qquad \dfrac{(ddu+dud+udd)}{\sqrt{3}} \qquad \dfrac{(duu+udu+uud)}{\sqrt{3}} \qquad$ uuu

$$\frac{(dds+dsd+sdd)}{\sqrt{3}} \qquad \frac{(dsu+uds+sud+sdu+dus+usd)}{\sqrt{6}} \qquad \frac{(suu+usu+uus)}{\sqrt{3}}$$

$$\frac{(dss+sds+ssd)}{\sqrt{3}} \qquad \frac{(uss+sus+ssu)}{\sqrt{3}}$$

sss

Colour

To explain the observed hadron multiplets

- colour must have 3 distinguishable values
- all hadrons are required to be colour neutral
  - there are 2 ways to make a hadron colour neutral
    1) colour+anticolour
       - red anti-red
       - blue anti-blue
       - green anti-green
    2) white
       - red+blue+green
       - anti-red + anti-blue + anti-green

Since colour is a quantum number associated with hadrons, it is natural to consider it as a conserved charge corresponding to a global gauge symmetry. Since it is possible to make colour neutrality with 3 charges, the group describing the gauge symmetry must have what is know as “rank 3”.

Perhaps the most obvious group is SU(3).

Quantum Chromodynamics

The most general $SU(3)_{colour}$ based gauge theory allows interactions which violate P and T symmetries. There is no theoretical reason to exclude such interactions, but current experimental limits on P and T violations in strong interactions tell us that any $SU(3)_{colour}$ P and T violation interactions are at least 8 orders of magnitude weaker then the P and T conserving QCD interactions. Various theoretical explanations for the absence of P and T violations (e.g. axions) have not been confirmed experimentally.

Quantum ChromoDynamics (QCD) is an $SU(3)_{colour}$ gauge theory based on 3 colour charges, needing 8 gauge bosons to mediate the transformations between the 3 colours. The P and T violating parts of the interaction Hamiltonian are excluded.

Gluons carry colour charge, unlike photons which do not carry electric charge.

$SU(3)_{colour}$ is thought to be an exact symmetry, but it is hard to set more than crude direct experimental limits on colour conservation and on the gluon mass:

- In any decay, colour conservation forced by colour confinement and energy conservation.
- $m_{gluon} < 10$ MeV