From quark model to quantum chromodynamics

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Isospin, strangeness and hypercharge

Isospin symmetry of strong interaction (pp, pn, nn) and STRANGE particles $\rightarrow$ Gell-Mann and Pais interpreted this particles with the following assumptions:

- strange particles $\rightarrow$ new quantum number= *strangeness* (S);
- $S = 0$ for leptons, nucleons and pions;
- S conserved in strong and electromagnetic interactions;
- S not conserved in weak interactions.

Gell-Mann e Nishijima proposed the relation

$$Y = B + S \qquad Q = I_3 + \frac{1}{2}Y$$

SU(3) as symmetry group (broken symmetry) to described particles

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}.$$

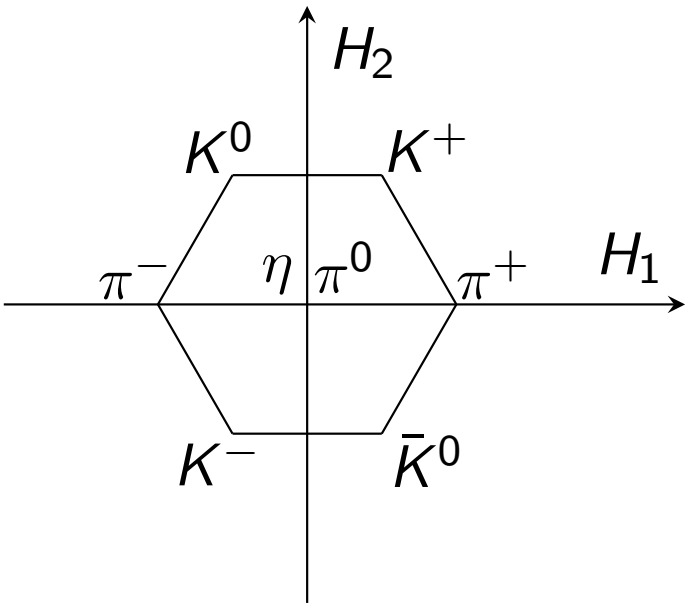
$$[\lambda_j, \lambda_k] = 2i f_{jk}{}^h \lambda_h$$

Cartan Subalgebra generators:

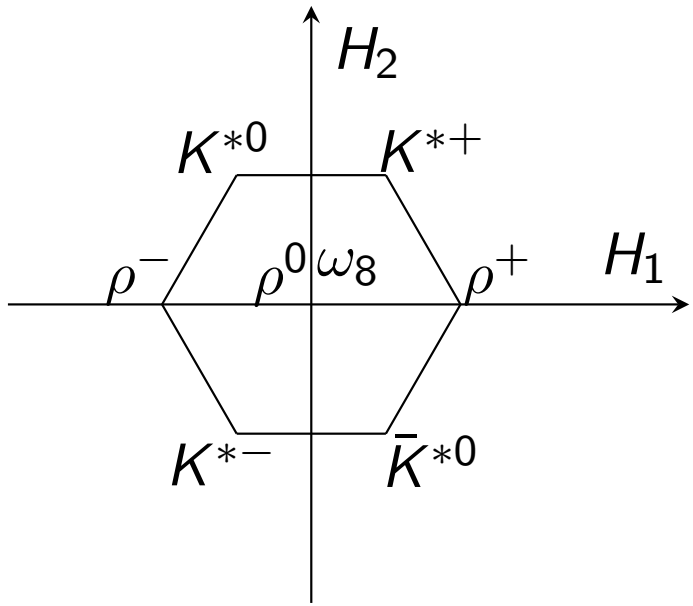
$$H_1 = \tfrac{1}{2}\lambda_3 = I_3 \qquad H_2 = \tfrac{1}{2}\lambda_8 = \tfrac{\sqrt{3}}{2} Y$$

Mesons

$\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$



(a) Pseudosclar mesons $J^P = 0^-$



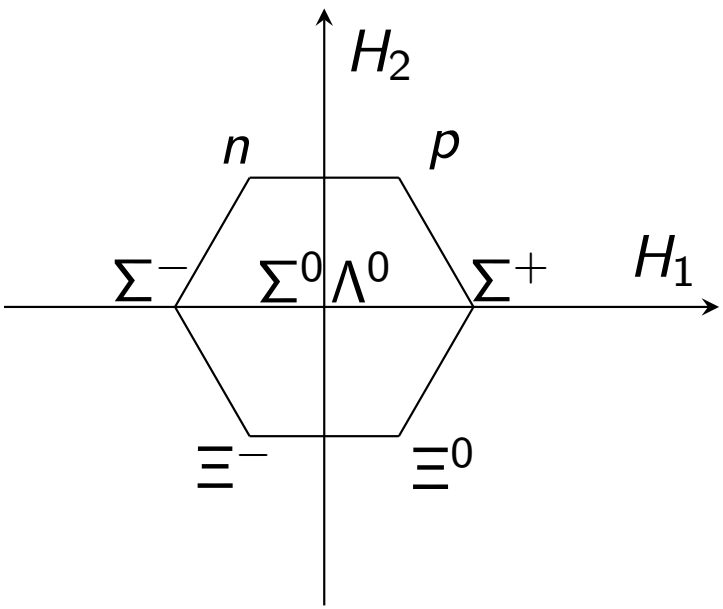
(b) Vectorial mesons $J^P = 1^-$

$$\eta' = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

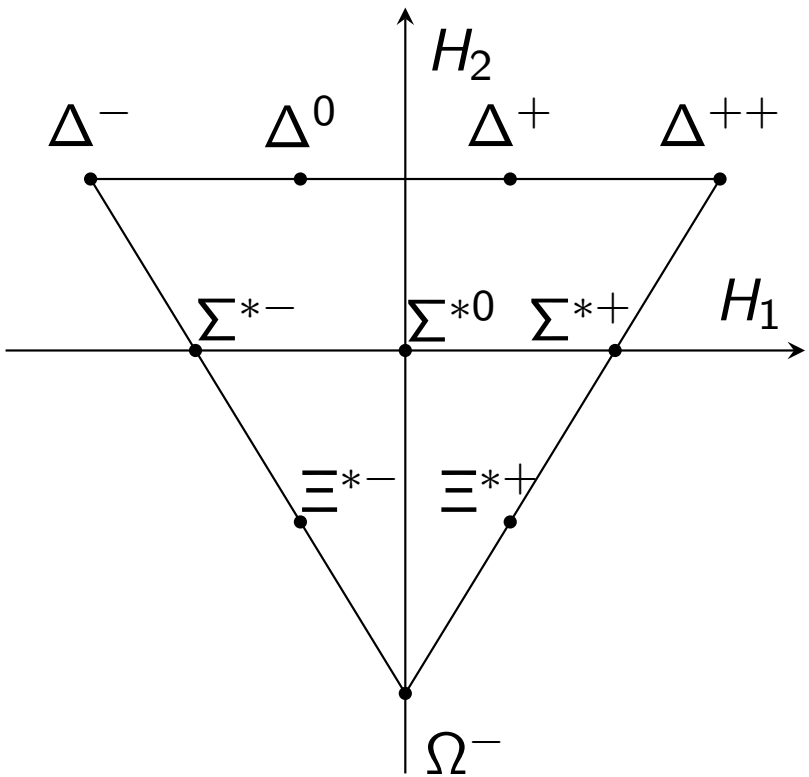
$$\omega_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

Baryons

$3 \otimes 3 \otimes 3 = 1 \oplus 8_S \oplus 8_A \oplus 10$



(c) Octet $J^P = \frac{1}{2}^+$



(d) Decuplet $J^P = \frac{3}{2}^+$

Gell-Mann - Okubo formula

Octec mass formula (baryons)

$$m_8(I, Y) = a + bY + c\left[I(I+1) - \frac{1}{4}Y^2\right]$$

Gell-Mann - Okubo relation

$$\frac{1}{2}(m_{\mathcal{N}} + m_{\Xi}) = \frac{1}{4}(3m_{\Lambda} + m_{\Sigma})$$

Electromagnetic split

U-spin generators

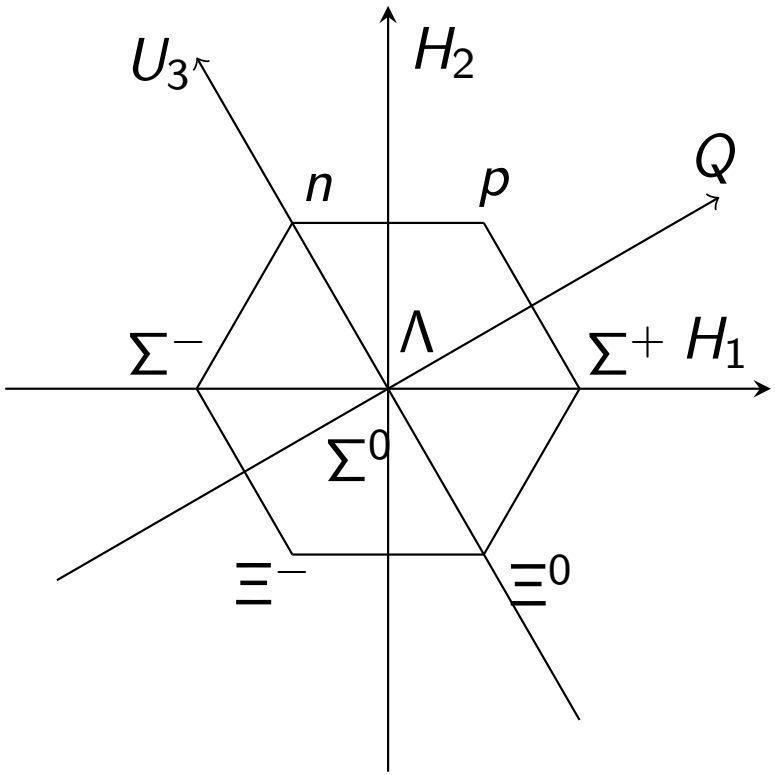
$$U_1 = \frac{1}{2}\lambda_6 \qquad U_2 = \frac{1}{2}\lambda_7$$

$$U_3 = \frac{1}{4}(\sqrt{3}\lambda_8 - \lambda_3) = \frac{1}{2}(\sqrt{3}H_2 - H_1)$$

$$[U_j, U_k] = i\epsilon_{jk}{}^h U_h$$

U-spin conserved in em interactions: $[U_j, Q] = 0 \ \forall j$

Electromagnetic split



Octet of baryons

$$m = m(I, Y) + \delta m(U, Q)$$

$$\delta m_p = \delta m_{\Sigma^+}\,, \quad \delta m_n = \delta m_{\Xi^0}$$
$$\delta m_{\Sigma^-} = \delta m_{\Xi^-}\,,$$

$$\delta m_n - \delta m_p = m_n - m_p\,,$$
$$\delta m_{\Xi^-} - \delta m_{\Xi^0} = m_{\Xi^-} - m_{\Xi^0}\,,$$
$$\delta m_{\Sigma^+} - \delta m_{\Sigma^-} = m_{\Sigma^+} - m_{\Sigma^-}\,.$$

Coleman-Glashow relation

$$m_n - m_p + m_{\Xi^-} - m_{\Xi^0} = m_{\Sigma^-} - m_{\Sigma^+}$$

Problems of the static model

Hadronic wave function

$$\psi = \phi_{flavour}\chi_{spin}\eta_{orbital}$$

1. Pauli principle's violation.
   Caso Δ^{++}:
   - $L = 0 \Rightarrow \eta_{orbitale}$ symmetric
   - $\Delta^{++} = uuu \Rightarrow \phi_{sapore}$ symmetric
   - $S = \frac{3}{2} \Rightarrow 3$ spin up $\Rightarrow \chi_{spin}$ symmetric
2. No free quark observed
3. Hadrons build with the scheme $q\bar{q}$ o qqq, but in principle we can't exclude scheme like qq o $qqqq$.

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QCD

In the same time $\rightarrow$ SLAC experiments (Deep inelastic scattering)

Parton model

Parton model $\rightarrow$ elastic scattering of elementary particles
Properties = asymptotic freedom, confinament

We need a gauge theory (as in QED)

Gauge principle

Particles interaction associated with the request of local phase invariance

It has to be non abelian to describe experiments!
New degree of freedom $\rightarrow$ color charge described by SU(3)