Hadrons

baryons

fermions
made up of three quarks
must have half-integer spins

mesons

bosons
made up of quark-antiquarks*
must have integer spins

* Bosons can be annihilated; strong interactions conserve the # of quarks

$$p + \overline{p} \rightarrow \gamma + \gamma$$

particle-antiparticle annihilation

- particle and antiparticle have opposite charges, baryon numbers, etc.
- they must have opposite intrinsic parities
- they must have opposite isospins

charge number

$$Q = -t_0 + \frac{A}{2}$$

baryon number

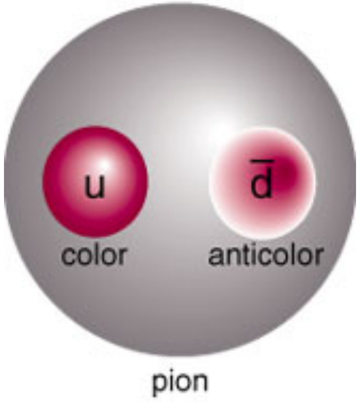
third component of isospin

$$\tau_{\pm}(\text{hadron}) \rightarrow \sum_{i=1}^{A} \tau_{\pm}(q_i)$$

$$|u\rangle \xrightarrow[\mathcal{C}]{} |\overline{u}\rangle \qquad |d\rangle \xrightarrow[\mathcal{C}]{} -|\overline{d}\rangle$$

Mesons

quark wave function of the pion



Consider π^- (t=1 and t_0=1). The only possible combination is

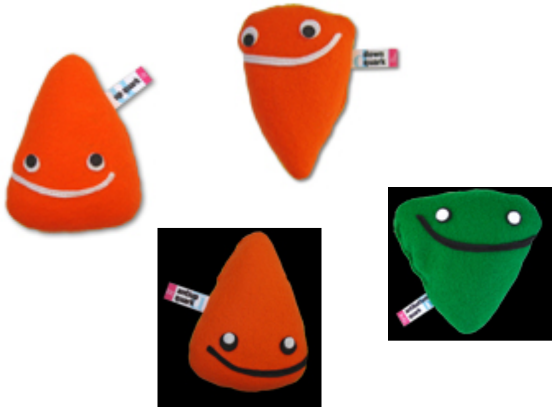
$$|\pi^-\rangle = |\bar{u}d\rangle$$

In general, it is possible to find several linearly independent components corresponding to the same t and t_0. The appropriate combination is given by isospin coupling rules. Furthermore, the wave function must be antisymmetric among the quarks. This problem is similar to that of a two-nucleon wave function!

T=1 triplet:

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\tau_-|\pi^-\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

$$|\pi^+\rangle = -|u\bar{d}\rangle$$



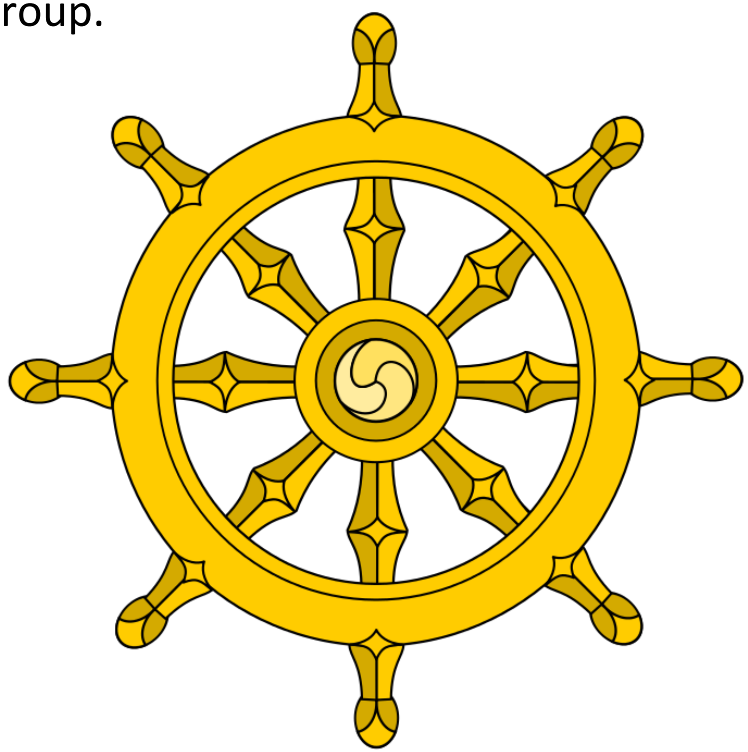
What about the symmetric combination?

T=0 singlet:

$$|\eta_0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$$

To produce heavier mesons we have to introduce excitations in the quark-antiquark system or invoke *s*- and other more massive quarks

The Eightfold Way is a term coined by Murray Gell-Mann for a theory organizing baryons and mesons into octets (alluding to the *Noble Eightfold Path* of Buddhism). The Eightfold Way is a consequence of flavor symmetry. Since the strong nuclear force affects quarks the same way regardless of their flavor, replacing one flavor of quark with another in a hadron should not alter its mass very much. Mathematically, this replacement may be described by elements of the SU(3) group. The octets and other arrangements are representations of this group.



The Dharma wheel
(represents the Noble Eightfold Path)

The lightest strange mesons are kaons or K-mesons. Since s-quark has zero isospin, kaons come in two doublets with *t*=1/2:

$$\left\{K^+(u\bar{s}),K^0(d\bar{s})\right\},\quad \left\{K^-(\bar{u}s),\bar{K}^0(\bar{d}s)\right\}$$

$$Y=\mathcal{A}+\mathcal{S}+\mathcal{C}+\mathcal{B}+\mathcal{T}$$

hypercharge

$$Q=-t_0+\frac{1}{2}Y$$

the SU(3) symmetry limit is met for massless u,d,s quarks

$$\pi^-(\bar{u}d)+p(uud)\to K^0(d\bar{s})+\Lambda(uds)$$

strangeness is conserved!

Pseudoscalar mesons

$$\vec{J}=\vec{\ell}+\vec{S},\quad \vec{S}=\vec{s}_q+\vec{s}_{\bar{q}}$$

$\vec{J}$	total angular momentum
$\vec{\ell}$	orbital angular momentum
$\vec{S}$	total spin

S can be either 0 or 1. The mesons with the relative zero orbital angular momentum are lower in energy. For the pion, *S*=0, hence *J*=0. Consequently, pions are “scalar” particles. But what about their parity? The parity of the pion is a product of intrinsic parities of the quark (+1), antiquark (-1) and the parity of the spatial wave function is 1. Hence, the pion has negative parity: it is a pseudoscalar meson.

With (u,d,s) quarks, one can construct 9 pseudoscalar mesons (recall our earlier discussion about the number of gluons!):

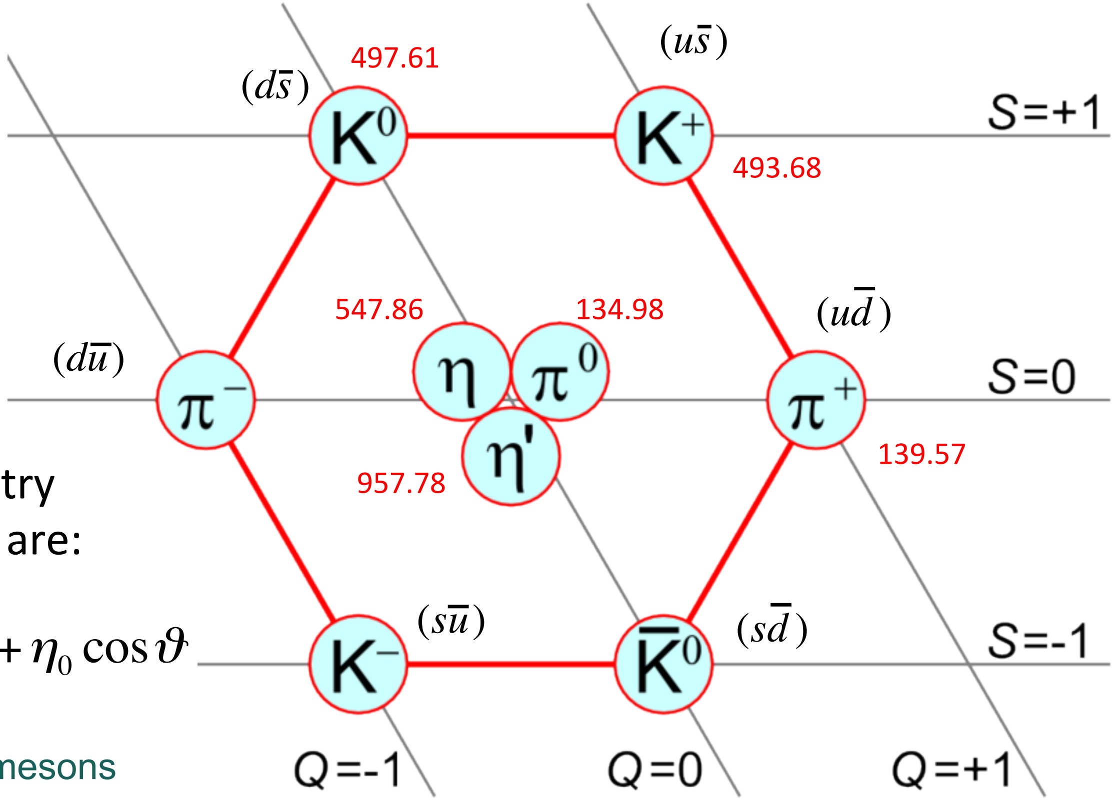
9 (nonet)=8 (octet)+1 (singlet)

Members of the octet transform into each other under rotations in flavor space (SU(3) group!). The remaining meson, η_0, forms a 1-dim irrep.

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

$$|\eta_8\rangle = \frac{1}{\sqrt{6}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle - 2|s\bar{s}\rangle\right)$$

$$|\eta_0\rangle = \frac{1}{\sqrt{3}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle\right)$$



In reality, since the SU_3 (flavor) symmetry is not exact one, the observed mesons are:

$$\eta = \eta_8 \cos\vartheta + \eta_0 \sin\vartheta \qquad \eta' = -\eta_8 \sin\vartheta + \eta_0 \cos\vartheta$$

ϑ – Cabibbo angle, ~11° for pseudoscalar mesons

masses are in MeV/c^2

The eta was discovered in pion-nucleon collisions at the Bevatron (LBNL) in 1961 at a time when the proposal of the Eightfold Way was leading to predictions and discoveries of new particles.

According to the quark model, can
a) 2-quark (qq)
b) 4-quark (qqqq)
c) 5-quark (qqqqq)
systems exist? Do not consider antiquarks.

What if antiquarks are also considered?

CP violation in Kaon decays

$$|K^0\rangle = |d\bar{s}\rangle \qquad |\overline{K^0}\rangle = |s\bar{d}\rangle$$

(*Q*=0)

$$\mathcal{C}|K^0\rangle = |\overline{K^0}\rangle \qquad \mathcal{P}|K^0\rangle = -|K^0\rangle$$

$$\mathcal{C}|\overline{K^0}\rangle = |K^0\rangle \qquad \mathcal{P}|\overline{K^0}\rangle = -|\overline{K^0}\rangle$$

$$\mathcal{CP}|K^0\rangle = -|\overline{K^0}\rangle$$

$$\mathcal{CP}|\overline{K^0}\rangle = -|K^0\rangle$$

Hmmm… Those are not CP eigenstates

$$|K_L^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right) \qquad |K_S^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right)$$

Long

Short

$$\mathcal{CP}|K_L^0\rangle = -|K_L^0\rangle$$

$$\mathcal{CP}|K_S^0\rangle = +|K_S^0\rangle$$

The main decay modes of K_S are: $K_S \to \overset{69\%}{\pi^+ + \pi^-} \quad \text{or} \quad \overset{31\%}{\pi^0 + \pi^0}$

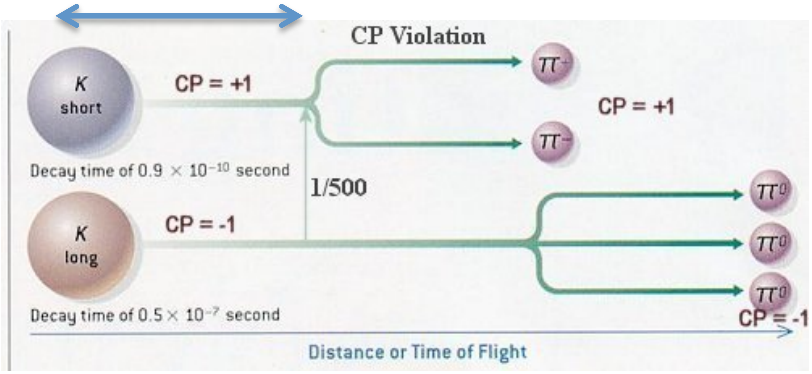
… and both decays conserve CP. What about K_L ?

$$\begin{aligned} K_L \rightarrow & \ \pi^+ + \pi^- + \pi^0 \\ & \ \pi^0 + \pi^0 + \pi^0 \\ & \ \pi^\pm + e^\mp + \nu_e \\ & \ \pi^\pm + \mu^\mp + \nu_\mu \end{aligned}$$

Three-body decay, very slow!

These decays are called semileptonic decays, producing one meson and two leptons. They account for about 67% of K_L decays compared to 33% for the 3π mode.

1m



$T(K_S)=(8.954 \pm 0.004) \times 10^{-11}$ s

$T(K_L)=(5.116 \pm 0.021) \times 10^{-8}$ s

Cronin & Fitch experiment, 1964

17 m beamline; K_S should not be observable more than a few centimeters down the beam line

Given the disparity of the lifetimes of the two kaon species, you expect to see only the long-lived version at the end of the beam tube, but they found about 1 in 500 decays to be 2-pion decays, characteristic of the short-lived species.