Quarks & Hadrons

Now to the strongly interacting particles

Quarks — Bound States of quarks

(hadrons)

they also interact via EM & weak forces
but we can often ignore them.

1960's saw plethora of new particles
↗ apparently new

Several dozen where observed by late 60's

Needed some unifying framework

"quark model" Gell-mann / Zweig all of
observed hadrons could be interpreted as bound
states of 3 quarks. → fundamental $\frac{1}{3}e + \frac{2}{3}e$
spin ½

Now, Universally Accepted

Then, serious doubts of unobservable ↙ directly quarks.

Changed
- Dynamics of individual quarks within proton observed
- QCD, explains why we can't see quarks
  → successfully described experimental results &

Another class of particles observed in nature

hadrons

n , p , π^+ π^- π^0

nucleons

Not elementary particles made of quarks

Bound together by strong interaction

Strong interaction (R G B colors)

$\bar{R}$ $\bar{G}$ $\bar{B}$ anti colors

quark pair

q R, G, B

$\bar{q}$ $\bar{R}$ $\bar{G}$ $\bar{B}$

g → massless

g ≡ Color/anti color

$R\bar{G}$

$\bar{q}(\bar{G})$

$q(R)$

An example more soon before

$g \to q\bar{q}$ → Same mass diff charges

6 quarks known to exist

$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$ $+2/3$ $-1/3$ → have seen ALL 6 experimentally

$\begin{pmatrix} m_J = 0.3 \\ 0.3 \end{pmatrix}$ $\begin{pmatrix} 1.5 \\ 0.5 \end{pmatrix}$ $\begin{pmatrix} 4.5 \\ 173 \end{pmatrix}$

→ All indirect from bound states or direct decays

No evidence for the existence of free quarks despite great efforts to find them
- moon rock
- oyster shells
- deep sea slug
- cosmic rays
- accelerators

However over 200 of quark bound states have been discovered.

Baryons qqq p Λ $1/2$ integer spin
$\bar{q}\bar{q}\bar{q}$ n Λ_c Λ_b

Mesons $q\bar{q}$ π k D B Υ
$u\bar{u}$ $u\bar{s}$ c b J/ψ
integer spin $u\bar{d}$ $s\bar{d}$
$d\bar{d}$

Strong & EM interactions $q+\bar{q}$ are only created or destroyed in pairs {QN associated w/ each quark flavor + Baryon #}

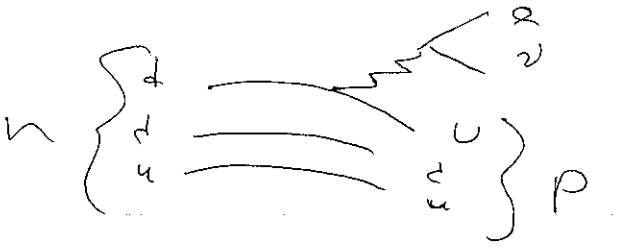
eg $p + p \rightarrow p + n + \pi^+$
(uud) $(uud) \rightarrow (uud)$ $(udd) + (u\bar{d})$

However for most interactions

eg β decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$

(udd) (uud) e^- $\bar{\nu}_e$



$N_u \neq N_d$

↖ indication of weak interaction

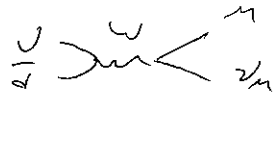
Pions

$\pi^{\pm}(140)$ ← MeV

$\pi^0(135)$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

↖ lifetime 10^{-8} s



$\pi^0 \rightarrow \gamma\gamma$

↖ lifetime $\sim 10^{-16}$ s

As for leptons Q.N. associated with flavors of quark

S - strangeness Baryon Number

charmness

Lifetimes of Particles Critical for understanding symmetry

↳ easy to measure

typical timescale associated w/ strong Interaction $\sim r_{nucl} \sim 10^{-23}$ s

However given set of Q.M. may not be lighter states available.

⇒ decay only via | weak interaction $10^{-7} - 10^{-10}$ s

| EM - powers of $10^{-16} - 10^{-21}$ s