

Elementary Particle Table

(1)

Why in pairs

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$l = e, \mu, \tau$$

$$l_R \quad \nu_R (=?)$$

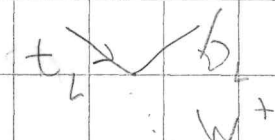
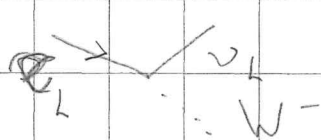
$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$u = u, c, t$$

$$\times 3 \text{ (colors)}$$

$$d = d, s, b$$

Photons and quark decays are mediated by emission



Dirac current

$$J_{ff'}^\mu = \bar{\psi}_f \gamma^\mu \psi_{f'} = \bar{\psi}_f \gamma^\mu \frac{(1-\gamma^5)}{2} \psi_{f'} + \bar{\psi}_f \gamma^\mu \frac{(1+\gamma^5)}{2} \psi_{f'} \\ = J_{Lff'}^\mu + J_{Rff'}^\mu$$

~~Left = eigenstate of negative helicity~~

~~R. photon~~



Charged Photons exist as observable stable particles

$$m = 0.5 \text{ MeV (a 0)}$$

e is stable, as the lightest charged particle (a conservation)

$$\mu \rightarrow e \bar{\nu}_e \nu_\mu \sim 100\% \quad \tau_\mu = 2.2 \text{ } \mu\text{s}$$

$$m = 105.7 \text{ MeV}$$

$$c\tau = 600 \text{ cm}!$$

$$\tau \rightarrow e \bar{\nu}_e \nu_\tau \quad 17\%$$

$$\mu \bar{\nu}_\mu \nu_\tau \quad 17\%$$

$$\nu_\tau \text{ hadron} \quad 66\%$$

$$M \sim 1777 \text{ MeV}$$

$$\tau_c = 290 \text{ fs}$$

$$c\tau \approx 9 \times 10^{-8} \text{ m} \approx 100 \text{ } \mu\text{m}$$

$\rightarrow$ 100 nm band of. decays visible

Quarks

$$m_u = 1 \text{ MeV } (2 \times m_e)$$

$$m_d = 4 \text{ MeV } (8 \times m_e)$$

$$m_s = 100 \text{ MeV}$$

$$m_c = 1.5 \text{ GeV}$$

$$m_b = 4.5 \text{ GeV}$$

$$m_t = 175 \text{ GeV}$$

Confinement: ~~quarks~~ we can observe only quark bound states: Hadrons

Mesons: $q\bar{q}$ bosons

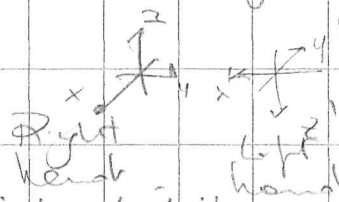
Baryons: $q_1 q_2 q_3$ } fermions
 $\bar{q}_1 \bar{q}_2 \bar{q}_3$

(top decays before binding $\sim 10^{-25} \text{ s}$)

Hadrons are further grouped according to Parity (charge conjugation) = $\bar{\psi}\psi$

- Spin
- Flavor color

Parity: symmetry of the particle wave function under reflection of axes



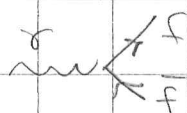
Each particle is a ψ eigenstate

$$\psi(x, y, z) = p \psi(x', y', z')$$

$$\psi^2 = 1 \Rightarrow p = \pm 1$$

$$\psi(x) = -\psi(x) \quad (\text{conjugate principle})$$

$$\text{Dirac equation} \quad \psi(\bar{\psi}) = \psi(x) = -1$$



$$\text{Conjugation} \quad \begin{cases} \psi(\psi) = +1(\psi) \\ \psi(\bar{\psi}) = -1(\bar{\psi}) \end{cases}$$

Bound States (positronium, hadrons) (2)

$$\phi(f \bar{f}') = \sum_{\substack{L=0 \\ \text{if } f=f'}} (-1)^L = (-1)^{L+1}$$

spherical harmonic

$$\phi(f_1 f_2 f_3) = \left(\frac{1}{f}\right)^3 (\dots) = 1 \quad \text{if } L=0$$

$$\phi(\bar{f}_1 \bar{f}_2 \bar{f}_3) = \left(\frac{1}{\bar{f}}\right)^3 (\dots) = -1$$

Charge conjugation: charges are charges and flavors

$$C|f\rangle = c|\bar{f}\rangle \quad (\text{not an eigenvalue, in general})$$

$$C^2|f\rangle = |f\rangle \quad c = \pm 1$$

Particles conjugate no charges whatsoever are C eigenstates

+ photon

$$C|\gamma\rangle = -|\gamma\rangle \quad (\text{conjugation principle})$$

+ $f \bar{f}$ bound states

$$C|f \bar{f}\rangle = (-1)^{L+S} |f \bar{f}\rangle$$

example: charmonium ($c \bar{c}$ bound state)

J	0	0	1	1
S	0	1	0	1
V	0	1	1	0/1/2
P	-1	-1	1	1
C	1	-1	-1	1

Name

η_c

Φ

h_c

χ_c

J^{PC}

0^{-+}

(1^{--})

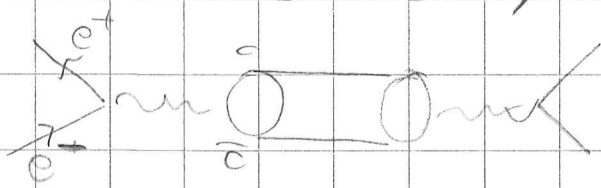
1^{+-}

$0^{++}, 1^{++}, 2^{++}$

$\rightarrow$ only available state for e^+e^- collision

$\psi(nS)$, ~~not~~ $n=1, 2, \dots$ ~~stable~~ same
quantum number as the χ : ~~...~~

- can be produced in e^+e^- collisions
- can decay into $e^+e^- / \mu^+\mu^-$ pairs



$\psi(1S)$ (also "J/ψ") $\rightarrow l^+l^-$ Br $\sim 6\%$
 $l = e, \mu$

$\psi(2S) \rightarrow \psi(1S) \times \sim 60\%$

~~BR~~ $e^+e^- / \mu^+\mu^- \sim 8 \times 10^{-3}$ each
 $e^+e^- \sim 3 \times 10^{-3}$

Figure Xapp Page

hadron organisation

(3)

Mesons	$\begin{cases} J^{PC} \\ J^{PC} \end{cases}$	$0^{+(-)}$ $1^{-(-)}$	Pseudoscalar Vector Meson
	$\begin{cases} J^P \\ J^P \end{cases}$	$\frac{1}{2}^{+}$ $\frac{3}{2}^{+}$	

in QCD spin-spin and spin-orbit interactions are quite significant!

$$m(P.S) \leq m(V.M)$$

$$m(\frac{1}{2}) \leq m(\frac{3}{2})$$

Vector Mesons decay (mostly) strongly to lighter pseudoscalars

$$\rho^{+(40)} \xrightarrow{\frac{1}{\sqrt{2}}} \pi^{+} \pi^{0} (136) |u\bar{d}\uparrow\uparrow\rangle \rightarrow |u\bar{d}\uparrow\downarrow\rangle |(\frac{u\bar{u} + d\bar{d}}{\sqrt{2}})\uparrow\downarrow\rangle$$

$$\rho^{0(40)} \xrightarrow{\frac{1}{\sqrt{2}}} \pi^{+} \pi^{-} (136) |c\bar{u}\uparrow\uparrow\rangle \rightarrow |c\bar{u}\uparrow\downarrow\rangle |(\frac{u\bar{u} + d\bar{d}}{\sqrt{2}})\uparrow\downarrow\rangle$$

Likewise, $\frac{3}{2}^{+}$ decay (preferentially) to $\frac{1}{2}^{+}$

$$|\Delta(1232)\rangle \rightarrow \pi N$$

$$|uud\uparrow\uparrow\rangle \xrightarrow{\Delta^{+}} |u\bar{d}\uparrow\downarrow\rangle_{\pi^{+}} |u\bar{u}\uparrow\downarrow\rangle_n$$

Exercise: Look in the PDG for ρ^{0} decay

(Can you prove or find a reason why $\rho^{0} \rightarrow \pi^{0} \pi^{0}$ is not allowed?)

P.S. and Δ^{++} baryons decay either weakly or strongly

$$K^{+} \rightarrow \pi^{+} \pi^{0} \quad (>99\%)$$

$$\pi^{+} \rightarrow \mu^{+} \nu \quad (>99.9\%)$$

$$n \rightarrow p e^{-} \bar{\nu}_e \quad (100\%)$$

Question: the kaon decay

$K^+ \rightarrow \pi^+ \pi^0$ involves only hadrons, yet it is a weak decay.

1) What empirical evidence shows it must be weak?

2) What ~~weak~~ (partially broken) symmetry forbids it to proceed through SI?

Flavor

Hadrons are also grouped based on flavor $SU(N)$ symmetries. N : number of flavors.

These are partial accidental symmetries,

States in a symmetry group should be indistinguishable.

Baryon symmetry:

- observed by Strong Interactions
- broken by weak, QED

Example

$SU(2)$: symmetry interchanging u and d quark ("Strong isospin")

$$m(p) \approx m(n) \approx 940 \text{ MeV} \quad (\Delta m = 1.3 \text{ MeV})$$

$$\hookrightarrow N = \begin{pmatrix} p \\ n \end{pmatrix}$$

$$\pi^+ (140) \quad \pi^0 (136) \quad \pi^- (140)$$

$$\pi = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$$

$$m(K^+) \approx m(K^0) \approx 490 \text{ MeV}$$

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}$$

$$\bar{K} = \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix}$$

$$\Delta(1232) \begin{pmatrix} \Delta^{++} \\ \Delta^+ \\ \Delta^0 \\ \Delta^- \end{pmatrix}$$

D^+, D^0

$$m(D^+) = 1870$$

$$m(D^0) = 1865$$

 $|c\bar{q}\rangle$

$$\bar{q} = \bar{u}, \bar{d}$$

 B^+, B^0

$$m(B^+) = 5280$$

$$m(B^0) = 5280$$

 $|\bar{b}q\rangle$

$$q = u, d$$

Small mass differences because

$$m_s - m_u \ll \Lambda_{QCD}$$

$$3 \text{ MeV}$$

$$200 \text{ MeV}$$

$$\alpha_{\text{em}} \ll \alpha_{\text{strong}}$$

(e.m. interactions responsible for all
most of few MeV differences)

$SO(3)$: isospin + spin

$m(s) \sim 100 \text{ MeV}$, $m_s - m_d \sim 100 \text{ MeV} \sim \Lambda_{QCD}$
badly violated symmetry

~~figure~~ figure multiplets $SO(3)$

(Does slightly better with heavy hadron)

$$m(D_s) = 1968 \text{ MeV}$$

$$m(D_s) - m(D^{*0}) \approx 100 \text{ MeV} (\sim m_s - m_u)$$

$$m(B_s) = 5370 ; m(B_s) - m(B^*) = 90 \text{ MeV}$$

Exercise:

(4)

Look in the PDG at $D^{*+}(10)$ decays

Explain why $D^{*0} \rightarrow D^+ \pi^-$ is not possible (e

$SU(4)$ pinching chain)

$SU(5)$

beauty

are only very badly broken because

$$m_b \gg m_c \gg m_{s,u,d}$$