$i \xrightarrow{H_I} f$

1 N ~~Fo~~ Decays

1,2 2 — N collisions.

$H_I = H_{EM} + H_W + H_{strong}$ Standard Model

$\Gamma(i \to f) \propto |M_{fi}|^2 \; \rho(E)$

$\downarrow$ H_I $\qquad$ $\downarrow$ Kinematics particles

leptons

$$\begin{array}{c} Q_{EM} = -1 \\ 0 \end{array} \begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \Big\} \text{ leptons}$$

SU(2) doublets

Quarks

$$\begin{array}{c} Q = +\frac{2}{3} \\ = -\frac{1}{3} \end{array} \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \Big\} \text{ quarks}$$

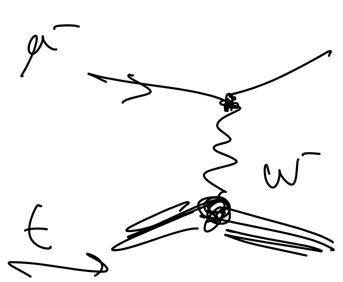
1^{st} $\qquad$ 2^{nd} $\qquad$ 3^{rd}

fam.

Fermions $S = \frac{1}{2}$

$m_e \simeq 0.5$ MeV $\qquad m_\mu \simeq 106$ MeV $\qquad m_\tau \simeq 1.8$ GeV

$m_{u,d,s} \simeq 10$ MeV $\qquad m_c \simeq 1.5$ GeV $\qquad m_{top} \simeq 170$ GeV



$\nu_\mu + p \to \mu^- + X$

$\nu_\mu + p \to e^- + X$
$= 0$

Q_{EM}

$$\begin{array}{c} +1 \\ 0 \end{array}\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix} \quad \begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$ anti-leptons

$$\begin{array}{c} +\frac{1}{3} \\ -\frac{2}{3} \end{array}\begin{pmatrix} \bar{d} \\ \bar{u} \end{pmatrix} \quad \begin{pmatrix} \bar{s} \\ \bar{c} \end{pmatrix} \quad \begin{pmatrix} \bar{b} \\ \bar{t} \end{pmatrix}$$ anti-quarks.

Nature: hadrons not quarks.
free states

Baryon: $q_1 q_2 q_3$

Mesons: $q_1 \bar{q}_2$

Pentaquarks: $q_1 q_2 q_3 q_4 q_5$

Molecule of mesons $q_1 \bar{q}_2 q_3 \bar{q}_4$

for each quark: 3 colors red, green, blue.

anti baryons $\bar{q}_1 \bar{q}_2 \bar{q}_3$

anti mesons $\bar{q}_1 q_2$

$\pi^+ \equiv |u\bar{d}\rangle$ $\quad Q = +1$ $\quad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$

$\pi^- \equiv |\bar{u}d\rangle$ $\quad Q = -1$

$p = |u\cancel{uu}\rangle$ $\quad Q = 3 \times \frac{2}{3} = \frac{6}{3} = +2$

$|uud\rangle$ $\quad Q = \frac{4}{3} - \frac{1}{3} = +1.$

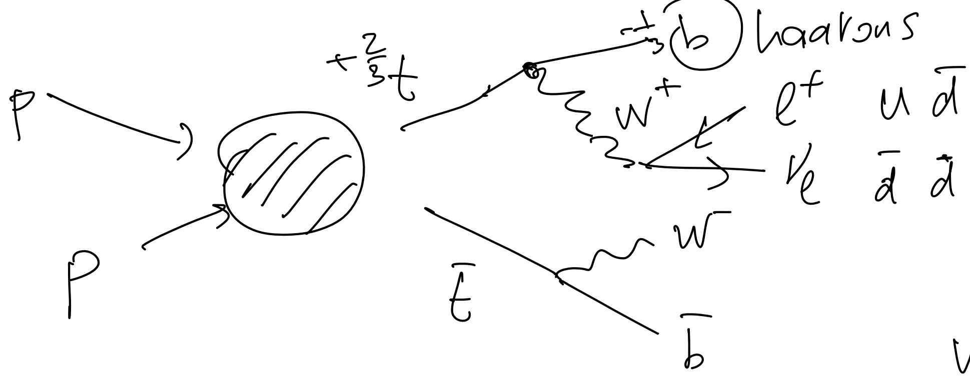
$p \equiv |uud\rangle$

$n \equiv |udd\rangle$ $\quad Q = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$

$B^- = |b\bar{u}\rangle$ $\quad -\frac{1}{3}, \bar{u} = -\frac{2}{3}$ $\quad \cancel{T^0 = |t\bar{u}\rangle}$ $\quad \cancel{t\bar{q}}$, $\cancel{t q_1 q_2}$

$B^0, B^+, \bar{B}^0$

no top hadron.



$W^+ \to e^+ \nu_e$

$\to \bar{d}^+ \bar{u}^0$

$t \to b \; W^+$

170 GeV   5 GeV   80 GeV

$\pi^\pm, \pi^0, p, n, e^-, \bar{g}$

Mediators of interactions

Bosons $S=+1$

- γ EM.
- $W^\pm, Z^0$ week.
- gluons Strong / QCD   Quantum Chromo Dynamics

scaler elementary particle. H Higgs boson.

$$\Gamma \propto |M_{fi}|^2 \, \rho(E)$$

Symmetries provide hints about H_I

symmetry: $T|\psi\rangle = |\psi'\rangle$

physical observable: $\hat{O}$ hermitian operator

$$\langle \hat{O} \rangle = \langle \psi | \hat{O} | \psi \rangle$$

$[T, H] = \emptyset$ T is a symmetry

H: hamiltonian.

$$\frac{d}{dt}\langle O \rangle = 0 \quad \longleftrightarrow \quad [O, H] = \emptyset$$

Transformations   Symmetry: unitary operators.

$$U^\dagger U = \mathbb{1} \iff U^\dagger = U^{-1}$$

Wigner Theorem: in QM all symm. are (anti-) unitary operators.

Types of symmetries

Continuous External Symm:

$U(a_1, \dots, a_N)$ = operates on $\vec{x}, t$ of system/state.

continuous function of $a_1, \dots, a_N$

Translation of $\vec{x}$ $\vec{P}$

t E Conserved quantity

Rotation of $\vec{x}$ $\vec{L}$

Nöther's theorem.

symmetry of the system $\longleftrightarrow$ Conserved quantity

Continuous Internal Symm:

$U(a_1, \dots, a_N)$ does not operate on $\vec{x}, t$ of system.

Isospin.

Rotation in internal space

$\vec{L} = \vec{r} \times \vec{P} \xrightarrow{QM} \vec{S}$, $\vec{J} = \vec{S} + \vec{L}$

classical mech

Discrete external symm:

Parity

unitary operator operates on $\vec{x}, t$

finite # of operators.

parity : $\vec{x} \rightarrow -\vec{x}$

Time inversion : $t \rightarrow -t$

Inversions :

$$I\psi = a\psi$$

$$I^2\psi = a^2\psi = \psi.$$

$a^2 = \pm 1$ $\qquad$ $I^\dagger = I^{-1}$

Discrete Internal Symm:

finite unit. operat. not on $\vec{x}, t$

Charge Conjugation $\mathbb{C}$

particle $\rightarrow$ anti-particle

Contin. Operator.

$$U(a_1 \cdots a_n) = e^{i \sum_i a_j T_j} = e^{i a_j T_j} \qquad T_j : \text{generators.}$$

$$U^\dagger U = \mathbb{1} \qquad U \simeq \mathbb{1} + i a_j T_j$$

$$\Rightarrow \boxed{T_j^\dagger = T_j} \quad \text{hermitian oper.}$$

$$\frac{d\langle U\rangle}{dt} = 0 \Rightarrow \frac{d}{dt}\langle T_j\rangle = \phi \Rightarrow \langle T_j\rangle \text{ conserved.}$$

$$U(\text{trans}) = e^{i\vec{p}\cdot\vec{x}} \qquad \vec{p} = \text{const.}$$

$$U(t\ \text{trans}) = e^{iEt} \qquad E = \text{const.}$$

$$U = e^{i\vec{L}\cdot\vec{\theta}} \qquad \vec{L} = \text{const.}$$

$$\vec{\theta} = (\theta_1, \theta_2, \theta_3)$$

$$U = e^{iaG} \quad 1 \text{ generator.}$$

$$\psi = \psi_1\psi_2$$

$$U\psi = U\psi_1\, U\psi_2 = e^{iaG}\psi_1\ e^{iaG}\psi_2$$

$$\simeq (1 + iaG)\psi_1\,(1 + iaG)\psi_2$$

$$= (1 + iag_1)\psi_1\,(1 + iag_2)\psi_2.$$

$$\simeq e^{ia(g_1+g_2)}\underbrace{\psi_1\psi_2}_{\psi}$$

$$g_{12} = g_1 + g_2 \qquad \text{Eigenvalues of generators.}$$

additive conservation law.

Inversion I

$$\psi = \psi_1 \psi_2$$

$$I\psi = I\psi_1 I\psi_2 = a_1 \psi_1 a_2 \psi_2 = (a_1 a_2) \underbrace{\psi_1 \psi_2}_{\psi}$$

multiplicative conservation law

$$\Rightarrow \quad a_{12} = a_1 \cdot a_2$$

	$n \rightarrow$	$p +$	$e^- +$	$\bar{\nu}_e$
B	1	1	0	0
L	0	0	1	-1
Q	0	1	-1	0

$$Q \longrightarrow U_{EM}(1)$$

Parity

γ: $P = -1$

π^-: $P = -1$

Conventional parity in SM:

e^-, ν_e, $P = +1$.

Quarks $P = +1$

$\left.\begin{array}{l}\text{antifermions : } P = -1 \\ \text{anti bosons : same parity as bosons}\end{array}\right\}$

Charge - Conjugation $\quad$ C-parity

particle $\longleftrightarrow$ antiparticle $\quad$ $e^+ \longleftrightarrow e^-$

$\pi^0 \longleftrightarrow ?$

$\mathbb{C}\psi = a\psi$

$\mathbb{C}^2\psi = a^2\psi = \psi \Rightarrow a = \pm 1$

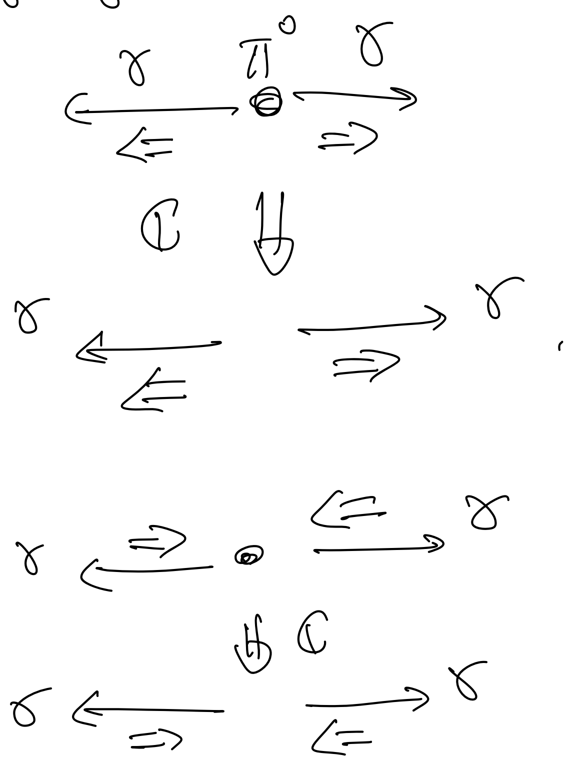
$n \to p\, e^- \bar{\nu}_e$ $\qquad n \neq \bar{n}$

$\bar{n} \to \bar{p}\, e^+ \nu_e$

neutral particles/states candidates to be eigenstate.

$\pi^0 \to \gamma\gamma$

Rest frame of π^0 $\qquad S_{\pi^0} = 0.$



$\bar{\pi}^0 \equiv \pi^0$ $\qquad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$

$i = \pi^0$

$f = \gamma\gamma.$

$C_{\pi^0} = C_{\gamma\gamma} = (C_\gamma)^2 = +1.$

$\Rightarrow C_{\pi^0} = +1$

Charge parity of pairs of particles.

boson – antiboson $\quad C = 1.$

fermion – antifermion $\quad C = -1$

$$\psi = \psi_{space} \psi_{spin} \psi_{intrinsic}$$