

# Title

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# 1 Intro to Particle Physics

## Four Fundamental Forces

- Strong (gluon)
- Weak (W, Z)
- Electromagnetic (photon)
- Gravity (graviton?)

The ‘Standard Model’ describe the first three forces and unifies the Strong and Weak Forces known as the ‘Electroweak’ force. So, the Standard Model does not include gravity.

## The Standard Model (SM)

- Basic building blocks: spin 1/2 particles (fermions)
- Interaction between them are mediated by force carriers: spin 1 particles (vector bosons)
- How particles get mass? → Higgs Boson (spin 0)

The Range of Forces:

- Strong:  $10^{-15}$  m
- Weak:  $10^{-18}$  –  $10^{-16}$  m
- EM:  $1/r^2$
- Gravity:  $1/r^2$

The ranges of forces are related by

$$R \frac{e^{-r/a}}{r^2}$$

where  $a \approx 10^{-15}$  m for the Strong and Weak forces.

**The Rise of Quantum Field Theory (QFT)** Relativity + Quantum Mechanics → QFT

	Macroscopic	Micro
SLOW	CM	Quantum Mechanics
FAST	Special Relativity	QFT

## QFT Discoveries

- Existence of anti-particles
- Spin-statistics theorem
- CPT Theorem (Charge conjugation, Parity, Time reversal)

## Units!

- Mass: (kg) → (eV) from  $E = mc^2$

$$m_e = 0.5 \times 10^6 \text{ eV}/c^2 \quad E_n = \frac{-13.6 \text{ eV}}{n^2}$$

$$m_p = 1 \text{ GeV}/c^2 \quad 1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

- Momentum:  $\frac{eV}{c} \rightarrow p = \frac{E}{c}$
- Energy: eV

**Matter Fermions** are divided into two groups:

- Leptons (electrons, muon, tau, neutrinos): Doesn't have the strong force
- Quarks (up, down, charm, strange, top, bottom): Feels the strong force

e.g. the proton is made of 2 up quarks and 1 down quark (uud) and the Neutron is (udd).

**Quarks** make up composite subparticles (Hadrons) are held together by the strong force.

- Mesons: 1 quark + 1 anti-quark ( $q\bar{q}$ ) e.g. pion, kaon...
- Baryons: 3 quarks ( $qqq$ ) e.g. proton, neutron

Quark charges:

- $Q = +2/3$  (up, charm, top)
- $Q = -1/3$  (down, strange, bottom)

**Leptons** are fundamental particles

- Charged electrically (-1)
  - electron (0.5 MeV)
  - muon (105 MeV)
  - tau (1.8 GeV)
- Neutral (neutrinos)
  - electron neutrino  $\nu_e$
  - muon neutrino  $\nu_\mu$
  - tau neutrino  $\nu_\tau$

**Crossing Symmetry**

$$A + B \rightarrow C + D \quad \text{Scattering}$$

$$A \rightarrow B + C + D \quad \text{Decay}$$

$$A + \bar{C} \rightarrow \bar{B} + D$$

e.g. Neutron Decay

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

Sum rules to think about:

- Baryon Number Conservation
- Lepton Number Conservation
- Electric Charge Conservation

another example:

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

$$p + e^- \rightarrow n + \nu_e$$

**Particle Conservation Laws**

## 2 Relativistic Kinematics

### Quiz 2 Review

1. The Baryon, Lepton, and Electric Charge are conserved in the Standard Model.
2. The Baryon and Lepton number ensure the stability of the proton.
3. In Neutron Decay  $n \rightarrow p + e^- + \bar{\nu}_e$ , the weak force is responsible for the decay.

	Strong	EM	Weak	Gravity
Strength	1	$10^{-2}$	$10^{-7}$	$10^{-40}$
Time scale	$10^{-23}$ sec	$10^{-16}$	$10^{-10}$	> yr

The decay rate is proportional to the coupling strength of the force  $\Gamma \propto \alpha^2$ . For the time scale is  $\tau$  it is inversely proportional:

$$\tau \propto \frac{1}{\Gamma}$$

4. The strong force is responsible for holding the nucleus together.
- 5.

**Experimental Discoveries** To discover and observe particles, there are typically three ways:

1. Scattering (cross section)
2. Decay (decay rate or lifetime)
3. Bound states (binding energy/mass)

**Relativistic Kinematics** 4-vectors

$$\begin{aligned} x^\mu &= (ct, x, y, z) && \text{space-time} \\ p^\mu &= (E/c, p_x, p_y, p_z) && \text{momentum} \end{aligned}$$

where  $x^\mu$  and  $p^\mu$  are the space-time (position) four-vector and energy-momentum four-vector.

**NOTE:** Total four-momentum is conserved in all interactions.  
Starting with the Lorentz invariant

$$p^\mu p_\mu = p^2$$

using the Einstein-summation convention

$$p^\mu p_\mu = \sum_{\mu=0}^3 p^\mu p_\mu = p^2$$

and the metric tensor

$$g^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

we can write the lower momentum vector as

$$p_\mu = p^\nu g_{\mu\nu}$$

thus

$$\begin{aligned} p^\mu p_\mu &= p^\mu p^\nu g_{\mu\nu} \\ &= \left(\frac{E}{c}\right)^2 + \mathbf{p} \cdot \mathbf{p}(-1) \\ &= \left(\frac{E}{c}\right)^2 - |\mathbf{p}|^2 \\ &= m^2 c^2 \end{aligned}$$

Using

$$E = \sqrt{|\mathbf{p}|^2 c^2 + m^2 c^4} \quad (2.1)$$

**Lorentz Transformation** At rest  $\mathbf{p} = 0$  and  $E = mc^2$ .  
In the Galilean transformation in the  $x$  direction:

$$\begin{aligned} x' &= x - vt \\ y' &= y \\ z' &= z \\ t' &= t \end{aligned}$$

where we assume absolute time, but in the Lorentz transformation:

$$\begin{aligned} x' &= \gamma(\beta ct + x) & \beta &= \frac{v}{c} \\ ct' &= \gamma(t - \beta x) & \gamma &= \frac{1}{\sqrt{1 - \beta^2}} \\ y' &= y \\ z' &= z \end{aligned}$$

In matrix form:

$$\Lambda = \begin{pmatrix} ct' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix}$$

and thus  $p^\mu p_\mu$  is invariant under Lorentz transformation.

**Massless particle:** From the energy momentum relation

$$E^2 = |\mathbf{p}|^2 c^2 + m^2 c^4$$

The massless particle has energy  $E = |\mathbf{p}|c$ . But we have to include the frequency (Planck) relation from quantum mechanics as well:

$$E = h\nu = \hbar\omega$$

And in the SM photons and neutrinos are massless thus

$$p^2 = p^\mu p_\mu = m^2 c^2 = 0$$

**Collisions** Non-relativistic vs. Relativistic

Non-relativistic:

- Elastic (KE conserved)
- Inelastic (KE not conserved)

Relativistic:

- Elastic (KE conserved) e.g. particle splitting into two
- Inelastic (KE not conserved) or Rest energy and mass e.g. colliding two particles to form a new particle
  - KE increases (Explosive)
  - KE decreases (Sticky)

In the extreme case:

$$A + B \rightarrow C \quad \text{inverse decay}$$

$$A \rightarrow B + C \quad \text{decay}$$

**Example**  $\pi^+ \rightarrow \mu^+ + \nu_\mu$  (decay)

The Rest energies are  $m_{\pi^+} = 135 \text{ MeV}/c^2$ ,  $m_{\mu^+} = 105 \text{ MeV}/c^2$ , and  $m_{\nu_\mu} = 0$ . But this energy is lost through the kinetic energy of the muon and muon-neutrino.

The momentum before is just the momentum of the pion

$$p_i = p_\pi = 0$$

since it is stationary. Afterward the momentum is split between the muon and neutrino

$$p_f = p_\mu + p_{\nu_\mu}$$

where energy and momentum is conserved:

$$\begin{aligned} \mathbf{p}_\mu &= -\mathbf{p}_\nu \\ m_\pi c^2 &= E_\mu + E_{\nu_\mu} \end{aligned}$$

**4-momentum conservation**

$$p_{\text{before}} = p_{\text{after}}$$

$$p_\pi = p_\mu + p_{\nu_\mu}$$

since the massless particle has no momentum from the energy momentum relation

$$\begin{aligned} p_\nu &= p_\pi - p_\mu \\ p_\nu^2 &= (p_\pi - p_\mu)^2 \\ &= p_\pi^2 - 2p_\pi p_\mu + p_\mu^2 \\ 0 &= m_\pi^2 c^2 + m_\mu^2 c^2 - 2 \frac{m_\pi c^2}{c} \frac{E_\mu}{c} \\ 2E_\mu m_\pi &= (m_\pi^2 + m_\mu^2) c^2 \\ E_\mu &= \frac{m_\pi^2 + m_\mu^2 - m_\nu^2}{2m_\pi} c^2 \end{aligned}$$

Another way is finding

$$p_\pi = p_\mu + p_\nu$$

rewritten as

$$p_\mu = p_\pi - p_\nu$$

squaring both sides gives

$$p_\mu^2 = p_\pi^2 - 2p_\pi p_\nu + p_\nu^2$$

and since  $p_\nu^2 = 0$  we have

$$p_\mu^2 = p_\pi^2 - 2p_\pi p_\nu$$

which implies

$$m_\mu^2 c^2 = m_\pi^2 c^2 - 2m_\pi E_\nu$$

the Planck relation tells us

$$E_\nu = |\mathbf{p}_\nu|c = |\mathbf{p}_\mu|c$$

thus

$$2m_\pi |\mathbf{p}_\mu|c = (m_\pi^2 - m_\mu^2)c^2$$

and

$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c$$

### Scattering experiments

- Head-on collision: (LHC)
- Fixed target collision: Beam of protons hitting a target (e.g. Carbon) (SLAC)

From momentum conservation, the head-on collision is more energy efficient as it loses the minimum amount of energy. The created particle is at rest, thus the energy is the rest energy. But the Fixed target collision has a higher energy loss since the particle loses energy since the created particle has kinetic energy.

e.g. The Anti-proton Discovery is due to the Bevatron colliding two protons to create an anti-proton

$$p + p \rightarrow p + p + p + \bar{p}$$

HW HINT:  $E_{cm} < E_{fixed}$

### 3 Symmetries

Quiz review:

3. The Energy of the large mass is

$$Mc^2 = E_1 + E_2 = 2\gamma mc^2$$

where the energy of the smaller masses are

$$E = \sqrt{|\mathbf{p}|^2 c^2 + m^2 c^4}$$

where  $|\mathbf{p}| = \gamma mv$  and  $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ . Thus the mass  $M > 2m$ .

4. Using the same thought from 3. we know that the rest mass of  $M$  is greater.

#### Lorentz Invariant

$$p^2 = m^2 c^2$$

From [Wikipedia](#): this is the lightlike vector. For the timelike  $p^2 > 0$  and spacelike  $p^2 < 0$ .

#### Symmetries

Equilateral triangles are symmetric under 3 axes where we can flip the triangle and it is still the same. For the square, we have 4 axes, and so and so forth. All of these objects are studied in [Group Theory](#).

**Group Theory** Group is a set of objects satisfying certain properties under an operation.

#### Properties

1. Closure: For  $a, b \in G$ ,  $a \cdot b \in G$
2. Identity: For any  $a \in G$ ,  $a \cdot I = I \cdot a = a$
3. Inverse: For each  $a \in G$ ,  $a \cdot a^{-1} = a^{-1} \cdot a = 1$
4. Associativity: For  $a, b, c \in G$ ,  $(a \cdot b) \cdot c = a \cdot (b \cdot c)$
5. (optional) Commutativity: For  $a, b \in G$ ,  $a \cdot b = b \cdot a$  AKA Abelian Group. Not all groups are commutative and thus are called non-Abelian groups.

#### Two Types of Groups

1. Finite: Finite number of elements. e.g.  $Z_2 = \{1, -1\} = \{I, r\}$  where  $r^2 = I$
2. Infinite: Discrete or continuous. e.g. set of integers under addition (discrete), set of real numbers under multiplication (continuous),  $U(1)$  (continuous)



**Examples** For an isoscale triangle  $Z_2 = \{1, -1\}$  and for an equilateral triangle  $Z_3 = \{0, 1, 2\}$  or the operation mod 3. Which is isomorphic to

$$\equiv \{1, \omega, \omega^2\}, \quad \omega = e^{2\pi i/3}$$

For the square

$$Z_4 = \{0, 1, 2, 3\} \equiv \{1, i, -1, -i\} \quad \text{or} \quad \{1, \omega, \omega^2, \omega^3\}$$

Thus for  $n$  elements.

$$Z_n = \{e^{i2\pi j/n}\}, \quad j = 0, 1, \dots, n-1$$

where all of these groups are Abelian.

**For**  $n \rightarrow \infty$  We get a circle as it has an infinite number of symmetries.  
In addition  $j \rightarrow \infty$

$$\frac{2\pi j}{n} = \theta$$

we get

$$U = e^{i\theta} = \cos \theta + i \sin \theta$$

where  $\theta \in [0, 2\pi]$ , and we have the  $U(1)$  group.

$$U^\dagger U = I \quad U^\dagger = (U^*)^T$$

where the dagger is the transpose of the complex conjugate (conjugate transpose).

## Standard Model

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$U(N)$  set of unitary  $N \times N$  matrices (non-Abelian in general except for  $N = 1$ ). Taking the determinant of the matrix

$$\det(U^\dagger U) = \det I = 1$$

and

$$\det(U^\dagger) \det(U) = 1 \quad \det(U^{*T}) = \det(U^*) = (\det U)^*$$

and

$$|\det U|^2 = 1 \\ \det U = e^{i\alpha} \quad \alpha \in [0, 2\pi]$$

Choosing the phase angle  $\alpha = 0$  we get

$$\det U = 1 \quad SU(N) \subset U(N)$$

$\otimes$  is a direct product: Two groups  $F$  and  $G$ . For  $f \in F$  and  $g \in G$  we have

$$(f, g) \in F \otimes G$$

The  $U(1)$  group is related to the photon  $\gamma$ , the  $SU(2)$  group is related to the weak force  $W^\pm, Z^0$ , and the  $SU(3)$  group is related to the strong force  $g$  (gluon).

**SU(2)** A set of  $2 \times 2$  matrices with a determinant of 1.  
Given the theorem

$$U = e^{iH}$$

for the hermitian matrix  $H$  where

$$U^\dagger U = 1 \rightarrow e^{-iH^\dagger} e^{iH} = 1$$

thus

$$H^\dagger = H$$

we take the determinant of  $U$ :

$$\det U = \det(e^{iH}) = e^{i \text{Tr } H} = 1 = e^0$$

thus  $\text{Tr } H = 0$ . This means that the Hermitian  $H$  is traceless.

## Pauli Matrices

traceless matrices

$$\begin{aligned}\sigma_1 &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\ \sigma_2 &= \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \\ \sigma_3 &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\end{aligned}$$

thus we can write the Hermitian matrix as

$$H = \frac{1}{2} \sum_i \theta_i \sigma_i = \frac{1}{2} \theta \cdot \sigma$$

where we have the group element of  $SU(2)$

$$U = e^{i\theta \cdot \sigma / 2}$$

## From QM

$$\mathbf{S} = \frac{\hbar}{2} \sigma$$

$$\begin{aligned}[S_y, S_z] &= iS_x \\ [S_z, S_x] &= iS_y \\ [S_x, S_y] &= iS_z [\sigma_i, \sigma_j] = 2i\epsilon_{ijk}\sigma_k\end{aligned}$$

where  $\epsilon_{ijk}$  is the Levi-Civita symbol.

$$\epsilon_{ijk} = \begin{cases} 1 & \text{if } (i, j, k) \text{ is an even permutation of } (1, 2, 3) \\ -1 & \text{if } (i, j, k) \text{ interchange any two indices } (3, 2, 1) \\ 0 & \text{otherwise any index is repeated} \end{cases}$$

thus

$$[S_i, S_j] = i\epsilon_{ijk} S_k$$

The Lie Algebra for  $SU(2)$  is  $SO(3)$  where both groups are isomorphic.

$$[L_i, L_j] = i\epsilon_{ijk} L_k \quad \mathbf{L} = \mathbf{r} \times \mathbf{p}$$

the generators of  $SU(2)$  is  $\sigma/2$ . For  $SU(3)$

$$U = e^{i\theta \cdot \lambda / 2}$$

where we have the Gell-Mann matrices  $\lambda$ . In general for  $SU(N)$



## Symmetries Part 2: Spin & Isospin

**Quiz 3 Review** SU(2) is the group of 2x2 unitary matrices with determinant 1. Using the basis vectors  $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$  and  $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$  we can write the group element as

$$\begin{pmatrix} a \\ b \end{pmatrix} = a \begin{pmatrix} 1 \\ 0 \end{pmatrix} + b \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

or the linear combination of the basis vectors. Thus the transformation is

$$\begin{pmatrix} a' \\ b' \end{pmatrix} = U(\theta) \begin{pmatrix} a \\ b \end{pmatrix} = e^{i\theta \cdot \sigma/2} \begin{pmatrix} a \\ b \end{pmatrix}$$

The Lie Algebra for SU(2) is

$$[J_i, J_j] = i\epsilon_{ijk} J_k$$

and

$$[J^2, J_i] = 0$$

for simultaneous eigenstates of  $|j, m\rangle$ .

$$J_z |j, m\rangle = m\hbar |j, m\rangle \quad J^2 |j, m\rangle = j(j+1)\hbar^2 |j, m\rangle$$

from the ladder operators

$$J_{\pm} = J_x \pm iJ_y$$

where these are not Hermitian (does not commute). Thus

$$\begin{aligned} J^2 &= J_x^2 + J_y^2 + J_z^2 \\ &= J_+ J_- + J_- J_+ + J_z^2 \end{aligned}$$

furthermore

$$J_{\pm} |j, m\rangle = \hbar \sqrt{(j \mp m)(j \pm m + 1)} |j, m \pm 1\rangle$$

where going up the ladder  $m \rightarrow m+1$  and going down the ladder  $m \rightarrow m-1$ . For fixed  $j$  there is a maximum and minimum  $m$  value

$$m_{max} = j \quad m_{min} = -j$$

so for example

$$J_+ |j, j\rangle = 0 \quad J_- |j, -j\rangle = 0$$

### Spin

$$j \equiv s = 1/2, \quad m \equiv m_s = \pm 1/2$$

The basis states are

$$\begin{aligned} (1/2, 1/2) &= \begin{pmatrix} 1 \\ 0 \end{pmatrix} = |\uparrow\rangle \quad m_s = 1/2 \\ (1/2, -1/2) &= \begin{pmatrix} 0 \\ 1 \end{pmatrix} = |\downarrow\rangle \quad m_s = -1/2 \end{aligned}$$

For the addition of spin

$$\frac{1}{2} \otimes \frac{1}{2} = ? \quad \mathbf{S} = \mathbf{S}_1 + \mathbf{S}_2 \quad S_{tot} = (S_1 + S_2), \dots, (S_1 - S_2) = 1, 0 \quad m_{s,tot} = 1, 0, -1, 0$$

### General Addition of Angular Momentum

$$|1, 1\rangle = |\uparrow\uparrow\rangle \quad |1, 0\rangle = \frac{1}{\sqrt{2}} |\uparrow\downarrow\rangle + \frac{1}{\sqrt{2}} |\downarrow\uparrow\rangle \quad |1, -1\rangle = |\downarrow\downarrow\rangle$$

finding the linear combination through basis transformation by using the resolution of the identity

$$\begin{aligned} |j, m\rangle &\rightarrow |j_1, m_1\rangle \otimes |j_2, m_2\rangle \\ &= \sum_{m_1, m_2} |j_1, m_1, j_2, m_2\rangle \langle j_1, m_1, j_2, m_2 | j, m \rangle \end{aligned}$$

where the bra-ket is the Clebsch-Gordan coefficient. thus

$$= \sum_{m_1, m_2} c_{m, m_1, m_2}^{j, j_1, j_2} |j_1, m_1, j_2, m_2\rangle$$

where  $m = m_1 + m_2$  and  $c_{m, m_1, m_2}^{j, j_1, j_2}$  is the Clebsch-Gordan coefficient.

**Example** For the  $S = 1$  state  $m = 1$

$$\begin{aligned} |1, 1\rangle &= |1/2, 1/2\rangle \otimes |1/2, 1/2\rangle \\ &= |1/2, 1/2, 1/2, 1/2\rangle \\ &= |\uparrow\uparrow\rangle \end{aligned}$$

For  $m = 0$  we have a linear combination of the basis states

$$\begin{aligned} J_- |1, 1\rangle &= \hbar\sqrt{2} |1, 0\rangle \\ \text{or } |1, 0\rangle &= \frac{1}{\hbar\sqrt{2}} J_- |1, 1\rangle \end{aligned}$$

the sum of the basis states is

$$\begin{aligned} J_- (|1/2, 1/2\rangle \otimes |1/2, 1/2\rangle) &= \hbar\sqrt{(1/2 + 1/2)(1/2 - 1/2 + 1)} |1/2, -1/2\rangle \otimes |1/2, 1/2\rangle \\ &\quad + |1/2, 1/2\rangle \otimes |1/2, -1/2\rangle \\ &= \hbar(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \end{aligned}$$

or

$$|1, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

for  $m = -1$  we have

$$J_- |1, 0\rangle = \hbar\sqrt{2} |1, -1\rangle$$

where

$$|1, -1\rangle = |1/2, -1/2\rangle \otimes |1/2, -1/2\rangle = |\downarrow\downarrow\rangle$$

Now for  $S = 0$ ,  $m = 0$  we have

$$|0, 0\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

since it is the way to make it orthogonal to  $|1, 0\rangle$ . Therefore

$$\frac{1}{2} \otimes \frac{1}{2} = 1 \oplus 0$$

Thus there are 3 triplet states  $m_s = 1, 0, -1$  and 1 singlet state  $m_s = 0$ .

## Isospin

$$m_p = 938.3 \text{ MeV}/c^2 \quad m_n = 939.6 \text{ MeV}/c^2$$

why are they so close? Heisenberg postulated an isospin state of a nucleon  $N$  as

$$N = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \alpha |p\rangle + \beta |n\rangle$$

with

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

the isospin state of the proton and neutron are

$$|p\rangle = \left| \frac{1}{2}, \frac{1}{2} \right\rangle \quad |n\rangle = \left| \frac{1}{2}, -\frac{1}{2} \right\rangle$$

1. Strong interactions preserve isospin symmetry
2. EM & Weak interactions do not preserve isospin symmetry

## Examples

Pions:  $\pi^+$ ,  $\pi^0$ ,  $\pi^-$  where the approximate symmetry is a triplet state

$$\begin{aligned} \pi^+ &= |1, 1\rangle & I &= 1, & I_3 &= 1 \\ \pi^- &= |1, 0\rangle & I &= 1, & I_3 &= 0 \\ \pi^0 &= |1, -1\rangle & I &= 1, & I_3 &= -1 \end{aligned}$$

$\Delta$ -baryons:

$$\begin{aligned} \Delta^{++} &= |3/2, 3/2\rangle & I &= 3/2, & I_3 &= 3/2 \\ \Delta^+ &= |3/2, 1/2\rangle & I &= 3/2, & I_3 &= 1/2 \\ \Delta^0 &= |3/2, -1/2\rangle & I &= 3/2, & I_3 &= -1/2 \\ \Delta^- &= |3/2, -3/2\rangle & I &= 3/2, & I_3 &= -3/2 \end{aligned}$$

where  $\Delta^{--}$  is an antiparticle of  $\Delta^{++}$ . We write from the highest to lowest from the empirical Gellman-Nishijima formula

$$Q = I_3 + \frac{1}{2}(B + S)$$

where  $Q$  is the charge,  $I_3$  is the third component of isospin,  $B$  is the baryon number, and  $S$  is the strangeness.

## Pions

Since a Pion is a *meson* and not a baryon, it has a baryon number of 0. Thus with no strangeness

$$S = 0 \quad B = 0$$

## Nucleons

$$S = 0 \quad B = 1$$

$$Q = \begin{cases} 1/2 + 1/2(1 + 0) = 1 & \text{proton} \\ -1/2 + 1/2(1 + 0) = 0 & \text{neutron} \end{cases}$$

For all elementary particles there is a general formula

$$Q = I_3 + \frac{Y}{2}$$

where  $Y$  is the hyper charge  $U(1)_Y$ .

## Power of Symmetry: Applications

1. Deuteron (neutron of deuterium): Two-Nucleon system

$$I = 1 \quad \text{or} \quad 0 \quad I_3 = 1, 0, -1 \quad \text{or} \quad 0 \quad (\text{singlet})$$

$$|1, 1\rangle = |p, p\rangle$$

$$|1, 0\rangle = \frac{1}{\sqrt{2}}(|p, n\rangle + |n, p\rangle)$$

$$|1, -1\rangle = |n, n\rangle$$

$$|0, 0\rangle = \frac{1}{\sqrt{2}}(|p, n\rangle - |n, p\rangle)$$

experimentally, we only see the singlet state because we see only one deuteron state. Thus we can only see a isospin state of  $I = 0$ .

**Two-nucleon potential**  $\propto \mathbf{I}_1 \cdot \mathbf{I}_2$  where we have the total isospin

$$\mathbf{I}^2 = (\mathbf{I}_1 + \mathbf{I}_2)^2 = \mathbf{I}_1^2 + \mathbf{I}_2^2 + 2\mathbf{I}_1 \cdot \mathbf{I}_2$$

where the  $s^2$  term is

$$s^2 = 1/2(1/2 + 1)\hbar^2 = \frac{3}{4}\hbar^2$$

Thus

$$\mathbf{I}_1^2 + \mathbf{I}_2^2 = \frac{3}{2}$$

and

$$\begin{aligned} \mathbf{I}_1 \cdot \mathbf{I}_2 &= \frac{1}{2}(\mathbf{I}^2 - 3/2)^{3/2} \\ &= \begin{cases} 1/2(1(1+1) - 3/2) = 1/4 & \text{triplet} \\ 1/2(0(0+1) - 3/2) = -3/4 & \text{singlet} \end{cases} \end{aligned}$$

## Symmetries Part 3: Scattering

### Quiz 5 Review For $j$

$$\frac{1}{2} \otimes \frac{1}{2} = 1 \oplus 0$$

For  $2j + 1$

$$2 \otimes 2 = 3 \oplus 1$$

Isospins of particles

1. pion: 1
2. deuteron: 0
3.  $\Delta$ -baryons: 3/2
4. nucleons: 1/2

The strong interaction preserves  $I$  and  $I_3$ , and the weak interactions do not preserve  $I$  and  $I_3$  (e.g. in beta decay the iso spin of the neutron (-1/2) go to an iso spin of the proton (1/2)). In E&M the isospin preserves only  $I$  and not  $I_3$  (e.g.  $\pi^0$  decay to two photons  $\gamma\gamma$ :  $I_3 = 0$  for the  $\pi^0$  and  $I_3 = 0$  for the two photons).

### Applications of Isospin: Nucleon-nucleon Scattering

$$p + p \rightarrow D + \pi^+$$

$$p + n \rightarrow D + \pi^0$$

$$n + n \rightarrow D + \pi^-$$

The relative probabilities of these processes: we get this from the amplitude  $A$  where the probability  $|A|^2$  is proportional to the cross section  $\sigma = \pi r^2$  (the cross section of a sphere, but this is not a solid sphere and rather a ‘fuzzy’ sphere). With the fact that ‘strong interactions preserve isospin’ we have the the ratio of the cross sections

$$\sigma_a : \sigma_b : \sigma_c$$

For all three processes the RHS the isospin is

$$I_{tot} = 0 \otimes 1 = 1$$

on the left hand side

$$I_{tot} = \frac{1}{2} \otimes \frac{1}{2} = 0 \quad \text{or} \quad 1$$

(a) The ratio of getting an isospin of 1 on the left hand side for the first process

$$|pp\rangle = |11\rangle$$

(c) for the third process

$$|nn\rangle = |1, -1\rangle$$

(b) The second is the linear combination of  $|10\rangle$  and  $|00\rangle$

$$|pn\rangle = \frac{1}{\sqrt{2}}(|10\rangle + |00\rangle)$$

the  $|00\rangle$  does not contribute to the isospin of 1. Thus the ratio of the probability is

$$A_a : A_b : A_c = 1 : \frac{1}{\sqrt{2}} : 1$$

and the ratio of the cross sections is

$$\sigma_a : \sigma_b : \sigma_c = 1 : \frac{1}{2} : 1$$





where the Clebsch-Gordan coefficient is

$$\langle 3/2, 1/2, 1/2, 1/2 | 3/2, 1/2 \rangle = \sqrt{\frac{2}{3}}$$

e.g. for the  $\pi^+p$  state

$$\begin{aligned} |\pi^+p\rangle &= |3/2, 3/2\rangle \\ \langle 3/2, 3/2, 1/2, 1/2 | 3/2, 3/2 \rangle &= 1 \end{aligned}$$

using the lowering operator

$$J_- |j, m\rangle = \hbar \sqrt{(j+m)(j-m+1)} |j, m-1\rangle$$

so

$$J_- |3/2, 3/2\rangle = \hbar \sqrt{3} |3/2, 1/2\rangle$$

applying the lower operator to  $J_{1-} + J_{2-}$  we get

$$\begin{aligned} J_- (|11\rangle \otimes |1/2, 1/2\rangle) &= \hbar \sqrt{2} |10\rangle \otimes |1/2, 1/2\rangle + \hbar \sqrt{1} |11\rangle \otimes |1/2, -1/2\rangle \\ &= \hbar \sqrt{2} |10\rangle \otimes |1/2, 1/2\rangle + \hbar |11\rangle \otimes |1/2, -1/2\rangle \end{aligned}$$

we then get

$$\begin{aligned} |3/2, 1/2\rangle &= \sqrt{2/3} |11\rangle \otimes |1/2, 1/2\rangle + \sqrt{1/3} |10\rangle \otimes |1/2, 1/2\rangle \\ &= \sqrt{2/3} |\pi^+p\rangle + \sqrt{1/3} |\pi^+n\rangle \end{aligned}$$

and the orthogonal state is

$$|1/2, 1/2\rangle = \sqrt{2/3} |\pi^+p\rangle - \sqrt{1/3} |\pi^+n\rangle$$

and so on for the other states. At the end we will find that the ratio of the total cross sections (adding up the matching elastic and exchange processes) is 3.

The amplitude has a factor

$$\langle \pi^+p | \pi^+p \rangle = \langle 3/2, 3/2 | 3/2, 3/2 \rangle = M_3$$

where for example

$$\begin{aligned} (\sqrt{2/3} \langle 3/2, 1/2 | - 1/\sqrt{3} \langle 1/2, 1/2 |) (\sqrt{2/3} | 3/2, 1/2 \rangle - 1/\sqrt{3} | 1/2, 1/2 \rangle) &= \\ = 2/3 \langle 3/2, 1/2 | 3/2, 1/2 \rangle - 1/3 \langle 1/2, 1/2 | 1/2, 1/2 \rangle &= \\ = 2/3 M_3 - 1/3 M_1 \end{aligned}$$

for  $M_3 \gg M_1$  the ratio is 4/9, and for  $M_3 \ll M_1$  the ratio is 1/3.

$SU(3)$

$$\begin{pmatrix} p \\ n \end{pmatrix} \quad SU(2) \text{ doublet}$$

where the spins are

$$\begin{aligned} p : uud \quad Q_u &= 2/3 \\ n : udd \quad Q_d &= -1/3 \end{aligned}$$

For the two spins

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

the isospins are

$$I = 1/2, \quad I_3 = 1/2 \quad \text{or} \quad -1/2$$

for the up and down quarks respectively. In reality we have six quarks

- Light quarks:  $u, d, s$
- Heavy quarks:  $c, b, t$

For the light quarks we have a  $SU(3)$  symmetry

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

the masses are all different:

$$m_u \approx 2 \text{ MeV}/c^2 \quad m_d \approx 4 \text{ MeV}/c^2 \quad m_s \approx 95 \text{ MeV}/c^2$$

so we have to add a flavor symmetry to the  $SU(2)$  isospin symmetry:

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix} \rightarrow \begin{pmatrix} u \\ d \end{pmatrix} \oplus s$$

or the  $SU(3)$  symmetry

$$SU(3)_f \rightarrow SU(2)_I \otimes U(1)_y$$

From  $SU(2)$  algebra:

$$[J_i, J_j] = i\epsilon_{ijk} J_k \quad J_i = \sigma_i/2$$

For the three pauli matrices

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Now for  $SU(3)$ : We know that the generators

$$U = e^{i\theta \cdot \lambda/2}$$

For  $SU(N)$  we have  $N^2 - 1$  generators. For  $SU(3)$  we have 8 generators. The Gell-Mann matrices are

$$\begin{aligned} \lambda_1 &= \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \lambda_2 &= \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} & \lambda_3 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \lambda_4 &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} & \lambda_5 &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} & \lambda_6 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \end{aligned}$$

## Symmetries Part 4: Young's Tableaux & Eightfold Way

### Quiz 6 Review

- (1) With respect to the QCD scale ( $\approx 200$  MeV) the masses of the quarks are divided into light and heavy quarks.
- (2) The effective mass is much larger than the mass of the light quark.
- (3)  $SU(2)$  is a subgroup of  $SU(3)$ .

For the  $SU(3)$ : a 3x3 unitary matrix with determinant 1. There are  $n^2 - 1 = 8$  generators where

$$U = e^{iH}$$

where  $H$  is the Hermitian matrix:

$$\begin{aligned} U^\dagger U &= 1 & H^\dagger &= H \\ \det U &= 1 & \text{tr } H &= 0 \\ \det M &= e^{\text{tr } \ln M} \end{aligned}$$

or Hermitian matrices are traceless.

**Gell-Mann Matrices** Starting with the Pauli matrices but in 3x3 form

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

and moving the sectors of the matrices we also get

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_9 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

and

$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \frac{1}{\sqrt{3}}$$

but  $\lambda_9$  is not linearly independent since it can be written as a linear combination of  $\lambda_3 + \lambda_8$ .

**Commutation Relation** For  $SU(2)$  we know

$$[J_i, J_j] = i\epsilon_{ijk} J_k$$

and for  $SU(3)$  we have

$$[J_i, J_j] = if_{ijk} J_k$$

where  $f_{ijk}$  are the structure constants.

**Subgroup** We know that  $SU(2) \leq SU(3)$  (where  $\leq$  means 'is a subgroup of'). So  $\{\lambda_1, \lambda_2, \lambda_3\}$  forms an  $SU(2)$  sub-algebra. Also

$$\begin{aligned} &\{\lambda_4, \lambda_5, a\lambda_3 + b\lambda_8\} \\ &\{\lambda_6, \lambda_7, a\lambda_3 + b\lambda_8\} \end{aligned}$$

are also  $SU(2)$  sub-algebras. NOTE that

$$SU(3) \neq SU(2) \otimes SU(2) \otimes SU(2)$$

### Isospin and Strangeness

$$\lambda_3/2 = \begin{pmatrix} 1/2 & 0 & 0 \\ 0 & -1/2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad I = 1/2$$

and the isospins are

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad I_3 = 1/2 \quad \text{or} \quad -1/2$$

and the strangeness is

$$S : I = 0$$

For  $\lambda_8$  we define a hypercharge  $y$  such that

$$\lambda_8/2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \frac{1}{\sqrt{3}} \frac{2}{\sqrt{3}}$$

and

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad y = 1/3$$

and for the strangeness  $S : y = -2/3$ . This is because the Gell-Mann-Nishijima formula

$$Q = I_3 + \frac{y}{2}$$

$$2/3 = 1/2 + 1/2(1/3) \quad -1/3 = 0 - 1/2(2/3)$$

For the triplet

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix} \quad I = 1/2, \quad I_3 = 1/2, -1/2, 0$$

and the anti-triplet

$$\begin{pmatrix} \bar{u} \\ \bar{d} \\ \bar{s} \end{pmatrix} \quad I = 1/2, \quad I_3 = 1/2, -1/2, 0$$

Mesons  $(q, \bar{q})$  in  $SU(3)$  is

$$3 \otimes \bar{3} = 8 \oplus 1$$

where the 8 is the octet and the 1 is the singlet. We can do this using the Young Tableaux. For  $SU(3)$  we have a 3 fundamental and  $\bar{3}$  anti-fundamental.

$N$	$N+1$
$N-1$	$N$
$N-2$	

Using Hook Law:

$$\dim = \frac{\prod_i N_i}{\prod_i h_i}$$

$$\frac{N(N+1)(N-1)N(N-2)}{1 \cdot 3 \cdot 4 \cdot 1 \cdot 2}$$

so

$$3 \otimes \bar{3} = \begin{array}{|c|} \hline 3 \\ \hline \end{array} \otimes \begin{array}{|c|} \hline 3 \\ \hline 2 \\ \hline \end{array} =$$

or

$$\begin{array}{|c|} \hline a \\ \hline \end{array} \otimes \begin{array}{|c|} \hline b \\ \hline c \\ \hline \end{array} = \begin{array}{|c|c|} \hline 3 & 4 \\ \hline 2 & \\ \hline \end{array} \oplus \begin{array}{|c|} \hline 3 \\ \hline 2 \\ \hline 1 \\ \hline \end{array} = \frac{3 \cdot 4 \cdot 2}{1 \cdot 3 \cdot 1} \oplus \frac{3 \cdot 2 \cdot 1}{1 \cdot 2 \cdot 3}$$

Goin from  $SU(3)$  to  $SU(2)$  we have

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix} \rightarrow \begin{pmatrix} u \\ d \end{pmatrix} + s$$

or

$$3 \rightarrow 2_1 + 1_{-2}$$

where the hypercharges are subscripts. So the octet is

$$\begin{aligned} 3 \otimes \bar{3} &= (2_1 + 1_{-2}) \otimes (2_{-1} + 1_2) \\ &= (2_1 \otimes 2_{-1}) \oplus (2_1 \otimes 1_2) \oplus (1_{-2} \otimes 2_{-1}) \oplus (1_{-2} \otimes 1_2) \\ &= (3_0 \oplus 1_0) \oplus 2_3 \oplus 2_{-3} \oplus 1_0 \\ &= 8 \oplus 1 \end{aligned}$$

This is called the eightfold way.

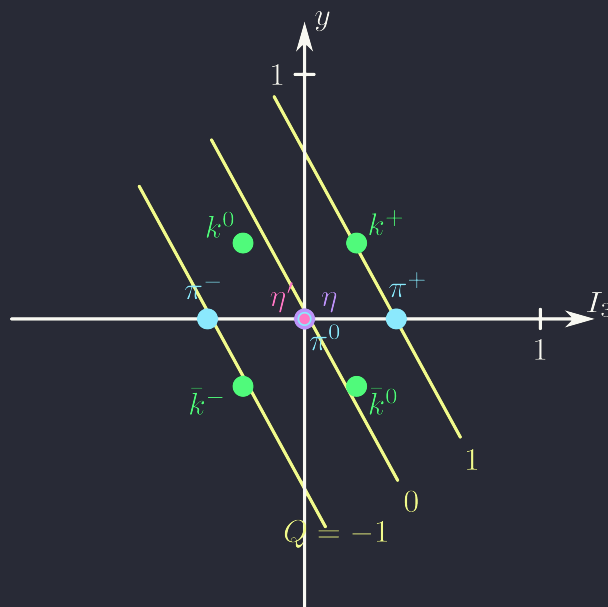


Figure 3.1: The eightfold way

**Eightfold way** Where  $\eta$  is a  $SU(2)$  singlet but a  $SU(3)$  octet. and  $\eta'$  is a  $SU(3)$  singlet.

If  $SU(3)_f$  was a good symmetry, expect all these 8 mesons to have similar mass. All of these obey up to a factor of 2.

**Baryons** (222) or  $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$ . The baryons are antisymmetric as each quark is a fermion. Using the Young Tableauex

$$3 \otimes 3 = \begin{array}{|c|} \hline a \\ \hline \end{array} \otimes \begin{array}{|c|} \hline b \\ \hline \end{array} = \begin{array}{|c|c|} \hline 3 & 4 \\ \hline \end{array} \oplus \begin{array}{|c|} \hline 3 \\ \hline 2 \\ \hline \end{array} = \frac{3 \cdot 4}{1 \cdot 3} \oplus \frac{3 \cdot 2}{1 \cdot 2} = 6$$

so

$$6 \otimes 3 = \begin{array}{|c|c|} \hline a & b \\ \hline \end{array} \otimes \begin{array}{|c|} \hline c \\ \hline \end{array} = \begin{array}{|c|c|c|} \hline 3 & 4 & 5 \\ \hline \end{array} \oplus \begin{array}{|c|c|} \hline 3 & 4 \\ \hline 2 \\ \hline \end{array} = \frac{3 \cdot 4 \cdot 5}{3 \cdot 2 \cdot 1} \oplus \frac{3 \cdot 4 \cdot 2}{1 \cdot 3 \cdot 1} = 10 \oplus 8$$

This is a 10-plet as shown in the figure.

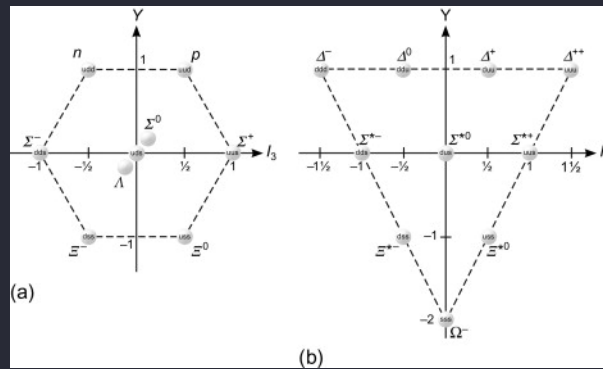


Figure 3.2: The 10-plet of baryons

## Symmetries Part 5: Parity

**Parity** (Discrete Symmetry) For a simple reflection on a  $z$  axis the point  $A = (x, y, z)$  goes to  $A' = (x, -y, z)$ . But for parity operation we go to  $P(A) = (-x, -y, -z)$  or in the general form

$$P(\mathbf{a}) = -\mathbf{a}$$

also known as inversion. Taking the parity again we get

$$P^2(\mathbf{a}) = P(-\mathbf{a}) = \mathbf{a}$$

Thus it has a discrete  $Z_2$  symmetry.

**Pseudo-vector** (axial vector) for a pseudo vector  $\mathbf{c}$

$$P(\mathbf{c}) = \mathbf{c}$$

where cross products (of two vectors) are pseudo-vectors. For example

$$\mathbf{c} = \mathbf{a} \times \mathbf{b}$$

and

$$P(\mathbf{c}) = P(\mathbf{a} \times \mathbf{b}) = (-\mathbf{a}) \times (-\mathbf{b}) = \mathbf{c}$$

e.g. of pseudo-vectors:

- Torque:  $\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$
- Angular momentum:  $\mathbf{L} = \mathbf{r} \times \mathbf{p}$
- Magnetic field:  $\mathbf{B} = \mathbf{E} \times \mathbf{v}$

But for the lorentz force

$$\mathbf{F} = q \left( \mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right)$$

the cross product of a vector and a pseudo-vector is a vector, so the lorentz force is a vector. Also from the general definition

$$P(\mathbf{F}) = \frac{q}{c} P(\mathbf{v}) \times P(\mathbf{B}) = \frac{q}{c} (-\mathbf{v}) \times (-\mathbf{B}) = -\mathbf{F}$$

The weak interaction violates parity...

**Scalar** For a scalar  $s = \mathbf{a} \cdot \mathbf{b}$  is invariant under parity:

$$P(s) = P(\mathbf{a} \cdot \mathbf{b}) = (-\mathbf{a}) \cdot (-\mathbf{b}) = \mathbf{a} \cdot \mathbf{b} = s$$

for a pseudo-scalar  $p$  (a dot product of a vector and pseudo-vector):

$$P(p) = P(\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c})) = P(\mathbf{a})P(\mathbf{b} \times \mathbf{c}) = -\mathbf{a}(\mathbf{b} \times \mathbf{c}) = -p$$

So the partities of the four types of quantities:

- Scalar:  $P(s) = s$
- Pseudo-scalar:  $P(p) = -p$
- Vector:  $P(\mathbf{v}) = -\mathbf{v}$
- Pseudo-vector:  $P(\mathbf{c}) = \mathbf{c}$



**Intrinsic Parity** The parity of a fermion is

$$P(\text{fermion}) = -P(\text{anti-fermion})$$

for bosons

$$P(\text{boson}) = P(\text{anti-boson})$$

For composite particles i.e. mesons  $q\bar{q}$  and baryons  $qqq$ :

$$P(\text{meson}) = -1 \quad \text{or} \quad (+1)(-1) = -1$$

Since mesons are two pairs (particle, antiparticle) the parity is always negative. For baryons we can only have a positive parity:

$$P(\text{baryon}) = (+1)^3 = +1$$

For spherical harmonics  $Y_l^m(\theta, \phi)$  under parity of each term:

$$\mathbf{r} \rightarrow -\mathbf{r} \quad \theta \rightarrow \pi - \theta \quad \phi \rightarrow \phi + \pi$$

so

$$P(Y_l^m(\theta, \phi)) = (-1)^l Y_l^m(\theta, \phi)$$

and for excited states

$$P = (-1)^l \times P(\text{ground state})$$

where  $l$  is the orbital angular momentum.

**Parity Violation** The  $\theta - \tau$  puzzle: given two particles

$$\begin{aligned} \theta^+ &\rightarrow \pi^+ + \pi^0 & P &= +1 \\ \tau^+ &\rightarrow \pi^+ + \pi^0 + \pi^0 & P &= -1 \end{aligned}$$

the same two particles are found to be the same particle  $K^+$  having the same mass and lifetime, but this violates the parity. To solve this puzzle came from the Columbia University known as Wu's experiment ([wikipedia](#)):



The Cobalt has a spin state of  $J = 5$ , the Nickel has spin  $J = 4$  and the spin states of the electron-antielectron pair is  $J = 1$ . The electron is always emitted in the direction opposite of the Cobalt spin, and when the magnetic field was inverted, the electrons were emitted in the opposite direction of nuclear spin. This breaks parity, because in the mirror world, the spin of the electron would be in the same direction as the nuclear spin.

**Helicity** From spin  $\mathbf{s}$  and momentum  $\mathbf{p}$  we can define the helicity

$$\begin{aligned} \lambda &= \frac{\mathbf{s} \cdot \mathbf{p}}{|\mathbf{s}| |\mathbf{p}|} \\ &= \begin{cases} +1 & \text{right-handed} \\ -1 & \text{left-handed} \end{cases} \end{aligned}$$

But this depends on the reference frame. e.g. for a case where  $\mathbf{p}$  is faster and in the same direction of  $\mathbf{s}$  the helicity is  $\lambda = +1$ , but in the reference frame faster than  $\mathbf{p}$  the helicity is  $\lambda = -1$ .

**Massless Particles** For massless particles the helicity is the same in all reference frames because the speed is always  $c$  and thus the helicity is well-defined. For an electron, we can get a frame where the momentum is different for changes in reference frames.

**Back to Wu's experiment** The spin of the electron and neutrino are in the same direction as the spin of the Cobalt and Ni.

**Note:** In the SM

- neutrinos are always left-handed;  $\lambda = -1$
- anti-neutrinos are always right-handed;  $\lambda = +1$

Thus the electron momentum is in the opposite direction of spin as shown in Figure 3.3

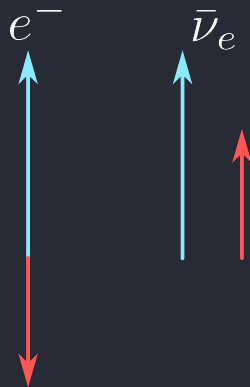


Figure 3.3: Wu's experiment

**Another Example** Pions and muons

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{or} \quad \pi^+ \rightarrow e^+ + \nu_e$$

From the comparison of masses

$$m_\pi = 140 \text{ MeV} \quad m_\mu = 105 \text{ MeV} \quad m_e = 0.511 \text{ MeV}$$

we would think the small mass reaction would be more likely due to the higher velocity, but this is not the case. For the pion the spin is 0, so the combination of spin will be in opposite directions. From Figure 3.4 we can see that the anti-lepton(anti particle) must be left-handed and thus the lepton must also be left-handed. This is a parity violation. Thus the less favored reaction  $u^+ + \nu_\mu$  is seen 99.7% of

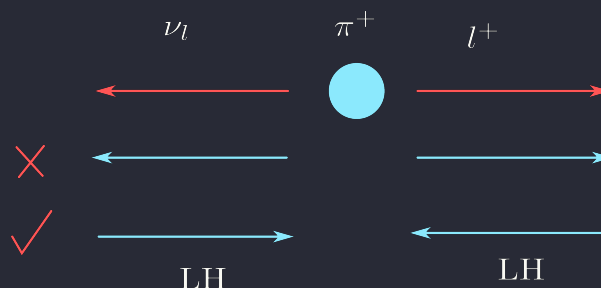


Figure 3.4: Pion decay

the time.

Anti-charged lepton has to be left-handed in this process of approximate

$$\Gamma \propto m_\ell^\beta$$

where  $\Gamma$  is the decay rate.

### Muon decay

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

This 3 body decay for a polarized muon (choosing the handedness of the muon) we have the following possibilities:

1. LH
2. RH

For maximum energy to the electron, the electron goes in one direction while the neutrinos go in the opposite direction as shown in Figure 3.5. From this the RH case is less favored than the LH case because of the helicity of the neutrinos.

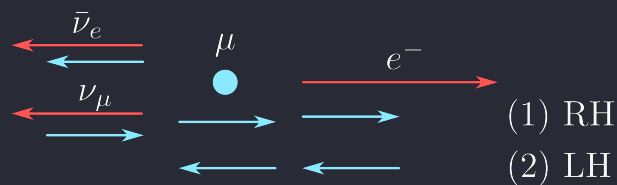


Figure 3.5: Muon decay

## Symmetries Part 6: G-Parity and CP Violation

### Quiz Review :

1. The neutrino is an eigenstate of parity (neutrino has handedness)

$$P|\nu\rangle_L = \pm|\nu\rangle_L \quad A|\psi\rangle = \lambda|\psi\rangle \quad P^2 = 1$$

but  $|\nu\rangle_R$  does not exist!

2. Charge Conjugation ( $C$ )

$$C|m\rangle = |\bar{m}\rangle$$

taking the charge conjugation twice

$$\begin{aligned} C^2|m\rangle &= C(C|m\rangle) = C|\bar{m}\rangle = |m\rangle \\ \implies C^2 &= 1 \implies C = \pm 1 \quad Z_z\text{-symmetry} \end{aligned}$$

So if  $|m\rangle$  is an eigenstate of  $C$  then

$$C|m\rangle = \pm|m\rangle = |\bar{m}\rangle \implies |m\rangle = \pm|\bar{m}\rangle$$

e.g. For charged particles:

$$C|\pi^+\rangle = |\pi^-\rangle$$

and for some neutral particles the charge conjugation is the same as the particle. One exception is the neutron

$$C|n\rangle = |\bar{n}\rangle$$

and for the violation of Charge conjugation: the neutrino

$$C|\nu\rangle_L = |\nu\rangle_L \times$$

here  $C$  must be violated (in weak interactions) but preserved in strong & EM interactions.

3. G-parity: defined as

$$G = CR$$

where  $R$  is a rotation. From the 8-fold way, we can get from  $\pi^+$  to  $\pi^-$  by reflecting it about the hypercharge axis or rotation by  $2\pi$  in the  $I_2$  axis and then taking its charge conjugation:

$$G = Ce^{i\pi I_2}$$

so

$$G|\pi^+\rangle = Ce^{i\pi I_2}|\pi^+\rangle = C|\pi^-\rangle = |\pi^+\rangle$$

finding the G-parity of  $K^+$ : from the 8-fold way (Figure 3.1) we know that rotating  $K^+$  actually gives us  $K^0$  so

$$G|K^+\rangle = Ce^{i\pi I_2}|K^+\rangle = C|K^0\rangle = |\bar{K}^0\rangle$$

**Neutral Pion Decay**  $\pi^0 \rightarrow \gamma + \gamma$  is a EM interaction (particle antiparticle pair:  $(u\bar{u} - d\bar{d})/\sqrt{2}$ ).

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

The parity on the LHS is  $P = -1$  and on the RHS  $P = (-1)^2 = +1$ . For the photon of spin:

$$S = 1, \quad S_z = +1, 0, -1$$

there is no longitudinal polarization  $S_z = 0$ , and the transverse polarization of the EM wave  $S_z = \pm 1$  is the helicity. So the helicity of the photons must be the same; either  $\lambda = |++\rangle$  or  $\lambda = |--\rangle$ . This is not an eigenstate of parity. The two photons must have aligned polarizations. We also need to find  $p$  in

$$\lambda = \frac{\mathbf{S} \cdot \mathbf{p}}{|\mathbf{S}||\mathbf{p}|}$$

where we know

$$p|+\rangle = |-\rangle \quad p|-\rangle = |+\rangle \quad p|++\rangle = |--\rangle$$

we can write a linear combination of the two states

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}(|++\rangle + |--\rangle)$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}(|++\rangle - |--\rangle)$$

for

$$P|\psi_1\rangle = |\psi_1\rangle \quad (\text{even parity})$$

$$P|\psi_2\rangle = -|\psi_2\rangle \quad (\text{odd parity})$$

This is similar to quantum optics where polarization is used:

$$|+\rangle = \frac{1}{\sqrt{2}}(|x\rangle + i|y\rangle) \quad |-\rangle = \frac{1}{\sqrt{2}}(|x\rangle - i|y\rangle)$$

we know the G parity is

$$G = (-1)^I$$

4. Pion decay to muon and neutrino: For the mesons

$$C = (-1)^{l+s}$$

where we have two types: Pseudoscalars ( $s = 0$ ) e.g.  $\pi, K$  with  $C = (-1)^l$  and vector mesons ( $s = 1$ ) e.g.  $\rho, K^*$  with  $C = (-1)^{l+1}$ . For  $\rho$  we know that  $I(\rho) = 1$  from the 8-fold way, as well as  $I(\eta) = 0$  so  $\rho \rightarrow 3\pi$  and  $\eta \rightarrow 2\pi$  are allowed.

**CP**

$$P|\nu_L\rangle = |\nu_R\rangle \times$$

$$CP|\nu_L\rangle = C|\nu_R\rangle = |\bar{\nu}_R\rangle$$

where the P is violated due to the handedness of the neutrino, but the CP is conserved. applying CP on to the charged pion decay:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

## CP Violation

For an oscillation of a neutral kaon  $K^0(d\bar{s})$  and  $\bar{K}^0(\bar{d}s)$ . Because K's are pseudoscalars:

$$P|K^0\rangle = -|\bar{K}^0\rangle \quad P|\bar{K}^0\rangle = |\bar{K}^0\rangle$$

and the charge conjugation is

$$C|K^0\rangle = |\bar{K}^0\rangle \quad C|\bar{K}^0\rangle = |K^0\rangle$$

and the CP is

$$CP|K^0\rangle = -|\bar{K}^0\rangle \quad CP|\bar{K}^0\rangle = -|K^0\rangle$$

which are not eigenstates of CP, so taking a linear combination of the two states

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \quad |K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

the CP of the two states are

$$CP|K_1\rangle = |K_1\rangle \quad CP|K_2\rangle = -|K_2\rangle$$

which are eigenstates of CP. Kaons decay to pions(lightest meson): to either 2 or 3 pions. From the phase space, the 2 pion decay is more likely than the 3 pion decay because faster particles are more likely to decay: A kaon with 490 MeV to  $2 \times 140 = 280$  MeV is more likely than  $3 \times 140 = 420$  MeV. The 2 pion decay has CP

$$CP|\pi^+\pi^-\rangle = (-1)^2|\pi^+\pi^-\rangle = |\pi^+\pi^-\rangle$$

$$CP|\pi^+\pi^-\pi^0\rangle = (-1)^3|\pi^+\pi^-\pi^0\rangle = -|\pi^+\pi^-\pi^0\rangle$$

so the 2 pion decay is CP even and the 3 pion decay is CP odd. If CP were conserved,

$$|K_1\rangle \rightarrow |2\pi\rangle \quad |K_2\rangle \rightarrow |3\pi\rangle$$

so we call this fast decay  $K_S$  meaning short ( $9 \times 10^{-11} \text{sec}$ ) and the slow decay  $K_L$  meaning long ( $5 \times 10^{-8} \text{sec}$ ) or

$$|K_1\rangle \equiv |K_S^0\rangle \quad |K_2\rangle \equiv |K_L^0\rangle$$

from a nobel prize winning experiment, a detector far away would be expected to see mostly  $K_L$  but the experiment showed that we saw some amount to the 2 pion decay:

$$|K_L^0\rangle = \frac{1}{\sqrt{1+\epsilon^2}}(|K_S^0\rangle + \epsilon|K_L^0\rangle)$$

where  $\epsilon = 2.3 \times 10^{-3}$  characterizes CP violation.

## Symmetries Part 7: CP Violation

### Quiz Review:

- matter-antimatter asymmetry: the  $\epsilon$  parameter measures the CP violation in the neutral kaon (hadronic decay mode). For the semi leptonic decay mode:

$$K_L^0 \rightarrow \pi^+ + e^- + \bar{\nu}_e$$

The CP symmetry shows

$$\rightarrow \pi^- + e^+ + \nu_e$$

And the rates for the decay modes differ by  $\epsilon$ . This relates to the matter-antimatter symmetry. (baryogenesis)  $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$  where  $n$  is the number of baryons/antibaryons/photons. In the SM  $\eta_{SM} \approx 10^{-20}$ , so the SM does not explain the matter-antimatter asymmetry fully. Finding the change in the rate of the process:

$$\frac{d\eta}{dt} \propto \Gamma(X \rightarrow Y + B) - \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

where the first decay rate  $\Gamma$  violates  $B$  (baryon number) for the charge conjugation

$$C(X \rightarrow Y + B) = \bar{X} \rightarrow \bar{Y} + \bar{B}$$

if  $C$  is conserved then

$$\Gamma(X \rightarrow Y + B) = \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

For CP violation: Quarks are chiral e.g.  $X \rightarrow q_L q_L, q_R q_R$  with (chirality:  $L$  and  $R$ ). We consider  $X$  as a linear combination:

$$X \rightarrow qq = q_L q_L + q_R q_R$$

The CP operation is

$$\begin{aligned} CP(X \rightarrow q_L q_L) &= \bar{X} \rightarrow \bar{q}_R \bar{q}_R \\ CP(X \rightarrow q_R q_R) &= \bar{X} \rightarrow \bar{q}_L \bar{q}_L \end{aligned}$$

so we can write this as a linear combination ( $r = \Gamma$ )

$$\begin{aligned} r(X \rightarrow qq) &= r(X \rightarrow q_L q_L) + r(X \rightarrow q_R q_R) \\ r(\bar{X} \rightarrow \bar{q}\bar{q}) &= r(\bar{X} \rightarrow \bar{q}_R \bar{q}_R) + r(\bar{X} \rightarrow \bar{q}_L \bar{q}_L) \end{aligned}$$

these are known as the Sakharov conditions:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium (forward process  $\neq$  backward process)

thus  $r(X \rightarrow Y + B) \neq r(Y + B \rightarrow X)$

- Rotation angles needed to describe mixing  $n$  generations of quarks: Cahibbo angles... in 2D we have 1 angle, in 3D we have 3 angles, and in 4D we have 6 angles. This is related to the number of orthogonal places in the space so  $n(n-1)/2$  angles are needed.

**$n \times n$  unitary matrix:** How many free parameters are there?  $n^2$  complex parts and  $n^2$  real parts thus  $2n^2$  parts. But the unitary matrix has  $n^2$  constraints (conditions) e.g.  $UU^\dagger = 1$  so we are left with  $n^2$  parameters. To find the number of physical parameters we add a phase which does not change the physical observables so we can have  $2n - 1$  phases e.g.

$$\begin{pmatrix} u \\ d \end{pmatrix} \rightarrow \begin{pmatrix} e^{i\alpha} u \\ e^{i\beta} d \end{pmatrix} e^{i\gamma}$$

here we can always add an overall phase hence the  $-1$ . so the free parameters are

$$n^2 - (2n - 1) = (n - 1)^2$$

and out these free parameters we subtract the number of rotation angles to get the number of physical phase angles.

$$(n - 1)^2 - \frac{n(n - 1)}{2} = \frac{(n - 1)(n - 2)}{2}$$

**$n \times n$  unitary matrix** is described by  $n(n - 1)/2$  rotation angles and  $(n - 1)(n - 2)/2$  phase angles. e.g. for  $n = 2$ : 1 rotation and 0 phase, for  $n = 3$ : 3 rotation and 1 phase. The 1 phase angle in the 3D case is the CP violation angle. This is known as the CKM matrix.

**For SU(3)** The euler rotation is:

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where

$$c_{12} \equiv \cos \theta_{12} \quad s_{12} \equiv \sin \theta_{12}$$

If the  $V_{CKM}$  is close to the identity, the rotation angles would be small, so the two bases are roughly the same. Experimentally we find that the rotation angles

$$\theta_{12} \approx 13^\circ \quad \theta_{23} \approx 2.4^\circ \quad \theta_{13} \approx 0.2^\circ \quad \delta \approx 70^\circ$$

which gives us the CKM matrix

$$V_{CKM} = \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}$$

or from the Feynman diagram

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

theses are called the Cabbibo-suppressed processes. There also is a Wolfenstein parameterization

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

for the mixing of the quarks of neutrinos:  $\nu_e, \nu_\mu, \nu_\tau$  we have the PMNS matrix

$$\begin{pmatrix} \nu'_e \\ \nu'_\mu \\ \nu'_\tau \end{pmatrix} = V_{PMNS} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

parametrized by  $(\theta_{12}, \theta_{23}, \theta_{13}, \delta)$  again. This is due to the angles of the rotations being much larger than the CKM matrix:

$$\theta_{12} \approx 34^\circ \quad \theta_{23} \approx 45^\circ \quad \theta_{13} \approx 8^\circ \quad \delta \approx ?$$

this is known as the flavor puzzle.





## Symmetries Part 8: Time Reversal

### Time Reversal Symmetry

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

the reverse process is hard to observe, but in principle it is possible in dipole moments.

**Dipole Moment** Two opposite charges  $\pm q$  separated by a distance  $d$ , we have electric field lines going from the positive to the negative charge which have a dipole moment

$$\mathbf{p} = q\mathbf{r}$$

for a uniform charge distribution we usually have a displacement vector

$$\mathbf{d} = \int d^3r \rho \mathbf{r}$$

### Magnetic dipole Moment

$$\mu = \int d^3r \mathbf{r} \times \mathbf{j}_q$$

where  $\mathbf{j}_q$  is the current density. A charged particle with a spin has a electric dipole moment

$$\mathbf{d} = d \frac{\mathbf{J}}{|\mathbf{J}|} \quad \mathbf{J} = \mathbf{L} + \mathbf{S}$$

and a magnetic dipole moment

$$\mu = u \frac{\mathbf{J}}{|\mathbf{J}|}$$

from Wigner-Eckart theorem. The Hamiltonian is

$$H = -(\mu \cdot \mathbf{B} + \mathbf{d} \cdot \mathbf{E}) = -\frac{1}{|\mathbf{J}|}(\mu \mathbf{J} \cdot \mathbf{B} + d \mathbf{J} \cdot \mathbf{E})$$

This is T-even because from the Schrodinger Eq  $H\psi = E\psi$  and invariant under T. Using Using Maxwell's equations

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho \\ t \rightarrow -t : \quad \mathbf{E} &\rightarrow \mathbf{E} \quad \text{T-even} \end{aligned}$$

and for second equation

$$\begin{aligned} \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ t \rightarrow -t : \quad \text{LHS doesn't change} \\ \text{RHS} \quad \mathbf{B} &\rightarrow -\mathbf{B} \quad \text{T-odd} \end{aligned}$$

To find if the angular momentum is T-even or T-odd we can use the definition of angular momentum:

$$\begin{aligned} \mathbf{L} &= \mathbf{r} \times \mathbf{p} \\ &= \mathbf{r} \times m \frac{d\mathbf{r}}{dt} \\ t \rightarrow -t : \quad \mathbf{v} &\rightarrow -\mathbf{v} \\ \mathbf{L} &\rightarrow -\mathbf{L} \quad \text{T-odd} \end{aligned}$$

for spin angular momentum we can visualize that from the right hand rule, the spin is T-odd i.e.  $\mathbf{S} \rightarrow -\mathbf{S}$  (T-odd). Adding the orbital and spin angular momentum we get the total angular momentum  $\mathbf{J}$  as T-odd. Since  $\mathbf{J}$  and  $\mathbf{B}$  are T-odd, we can deduce that  $\mu$  is T-even (odd times odd is even, and even times odd is even). By the same logic  $\mathbf{d}$  is T-odd.

**ACME Experiment** The limit of the electron dipole moment is

$$d_e < 8 \times 10^{-30} e.cm$$

and for the neutron dipole moment

$$d_n < 10^{-27} e.cm$$

**Axions(Not in Textbook)** A hypothetical particle: The Langrangian for fundamental particle is

$$\mathcal{L} = \theta G^{\mu\nu} G_{\mu\nu}$$

the electromagnetic field tensor is

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

where the magnetic field is

$$\mathbf{B} = \nabla \times \mathbf{A}$$

and

$$A^0 = \rho = F^{\mu\nu} F_{\mu\nu}$$

the Gluon field tensor

$$G^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

and  $\theta$  is T-odd. Experimentally we find that  $\theta < 10^{-10}$  (Strong CP problem). ADMX experiment is currently ongoing.

**CPT Theorem** All Observables must be CPT invariant in a Lorentz-invariant theory. Sometimes C, P, or T are violated, but CPT is always conserved. As a result, all anti-particles have the same mass as particles (Tested by LHC alpha experiment).

# Homework 1

Due 1/24

## 1. Gravity vs. E&M

Given the force of gravitational attraction

$$\mathbf{F}_g = -\frac{Gm_1m_2}{r^2}\hat{\mathbf{r}}$$

and the force of electrostatic repulsion

$$\mathbf{F}_e = \frac{1}{4\pi\epsilon_0} \frac{q_1q_2}{r^2} \hat{\mathbf{r}}$$

The ratio of the two forces between two electrons is

$$\frac{F_g}{F_e} = \frac{4\pi\epsilon_0 G m_e^2}{q_e^2}$$

Using the values for the constants

$$G = 6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2, \quad \epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2/\text{N m}^2$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}, \quad q_e = 1.60 \times 10^{-19} \text{ C}$$

we find

$$\boxed{\frac{F_g}{F_e} = 2.40 \times 10^{-43}}$$

this tells us that the denominator (the electrostatic force) is *much* larger than the numerator (the gravitational force), which convinces us that gravitational forces are negligible for elementary particles.

## 2. Mesons and Baryons

- (a) For mesons, you can have  $n$  possible quarks and  $n$  possible antiquarks, thus there are  $\boxed{n^2}$  combinations.

For baryons order does not matter we have to make sure not to double count instances such as  $(uud)$  and  $(udu)$ : This is essentially a combination problem with the solution

$$\binom{n}{3} = \frac{n!}{3!(n-3)!} = \boxed{\frac{n(n-1)(n-2)}{6}}$$

- (b) Given the 6 flavors of quarks, we would expect  $6^2 = 36$  mesons and  $\binom{6}{3} = 20$  baryons.
- (c) We haven't found all of them because of energy required to observe the heavier particles. In the Particle Data Group website, the heaviest baryon is in the order of 6000 MeV and the LHC has a beam energy of 6.5 TeV and the energy consumption is about 1.3 TWh per year compared to the global energy consumption of 20 000 TWh per year ([source](#)). In addition to the enormous energy required to produce these particles, they are also very unstable and decay very quickly thus detecting them require us to measure at very small time scales.

## 3. Global Conservation Laws

- (a)  $n \rightarrow \bar{p} + e^+ + \nu_e$   
not valid: violates Baryon number conservation

(b)  $\nu_e + n \rightarrow p + e^-$ 

valid

(c)  $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ 

valid

(d)  $\mu^- \rightarrow e^- + \gamma$ 

not valid because it violates electron and muon lepton number conservation

(e)  $e^+ + e^- \rightarrow \gamma$ 

valid

4. Nuclear  $\beta$ -decay

(a)

$${}^A_Z X \rightarrow {}^A_{Z+1} Y + e^-$$

From the conservation of momentum

$$p_X^\mu = p_Y^\mu + p_e^\mu \quad \text{or} \quad p_Y^\mu = p_X^\mu - p_e^\mu$$

squaring both sides

$$p_Y^2 = p_X^2 + p_e^2 - 2p_X \cdot p_e$$

and since

$$p_X^2 = m_X^2 c^2, \quad p_Y^2 = m_Y^2 c^2, \quad p_e^2 = m_e^2 c^2$$

and

$$p_X p_e = \frac{E_X}{c} \frac{E_e}{c} - \mathbf{p}_X \cdot \mathbf{p}_e$$

but we know that particle  $X$  has momentum  $\mathbf{p}_X = 0$  and rest mass  $E_X = m_X c^2$  so

$$m_Y^2 c^2 = m_X^2 c^2 + m_e^2 c^2 - 2m_X E_e$$

solving for the Energy of the outgoing particle is

$$E_e = \frac{m_X^2 + m_e^2 - m_Y^2}{2m_X} c^2$$

to find the momentum of the outgoing electron we use energy-momentum relation

$$E_e^2 = |\mathbf{p}_e|^2 c^2 + m_e^2 c^4$$

or

$$|\mathbf{p}_e|^2 = \frac{E_e^2}{c^2} - m_e^2 c^2$$

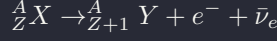
using the energy of the outgoing electron we found earlier:

$$\begin{aligned} |\mathbf{p}_e|^2 &= c^2 \left( \frac{m_X^2 + m_e^2 - m_Y^2}{2m_X} \right)^2 - m_e^2 c^2 \\ &= \frac{c^2}{4m_X^2} (m_X^2 + m_e^2 - m_Y^2)^2 - \left( \frac{c^2}{4m_X^2} \right) 4m_X^2 m_e^2 \\ &= \frac{c^2}{4m_X^2} (m_X^4 + m_e^4 + m_Y^4 + 2m_X^2 m_e^2 - 2m_X^2 m_Y^2 - 2m_e^2 m_Y^2 - 4m_X^2 m_e^2) \\ &= \frac{c^2}{4m_X^2} (m_X^4 + m_e^4 + m_Y^4 - 2m_X^2 m_e^2 - 2m_X^2 m_Y^2 - 2m_e^2 m_Y^2) \end{aligned}$$

and therefore the momentum of the outgoing electron is

$$|\mathbf{p}_e| = \frac{c}{2m_X} \sqrt{m_X^4 + m_e^4 + m_Y^4 - 2m_X^2 m_e^2 - 2m_X^2 m_Y^2 - 2m_e^2 m_Y^2}$$

(b) For the decay including an anti-neutrino



For the massless neutrino, the energy is

$$E_\nu = |\mathbf{p}_\nu|c$$

or from planck's relation

$$E_\nu = h\nu = \frac{hc}{\lambda}$$

so the energy of the neutrino is

$$E_\nu = \frac{6.63 \times 10^{-34} \text{ J s} \cdot 3 \times 10^8 \text{ m s}^{-1}}{10^{-15} \text{ m}} = 1.99 \times 10^{-10} \text{ J} = 1240 \text{ MeV}$$

and the momentum of the neutrino is

$$|\mathbf{p}_\nu| = \frac{E_\nu}{c} = \frac{1.99 \times 10^{-10} \text{ J}}{3 \times 10^8 \text{ m s}^{-1}} = 6.63 \times 10^{-19} \text{ kg m s}^{-1} \quad \text{or} \quad 1240 \frac{\text{MeV}}{c}$$

This is much larger compared to the typical neutrino energy (keV). This means that the neutrino could not have come from inside the nucleus.

Using the Heisenberg uncertainty principle

$$\Delta p \Delta x \geq \frac{h}{4\pi} \quad \text{or} \quad \Delta p \geq \frac{h}{4\pi \Delta x}$$

and the typical size of a nucleus is  $\Delta x \approx 1 \times 10^{-15} \text{ m}$  so

$$\Delta p \geq \frac{6.63 \times 10^{-34} \text{ J s}}{4\pi \cdot 10^{-15} \text{ m}} = 0.53 \frac{\text{J}}{\text{m/s}}$$

or in more convenient units  $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$  and  $c = 3 \times 10^8 \text{ m/s}$ :

$$\Delta p \geq 0.53 \frac{\text{J}}{\text{m/s}} \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}} \frac{3 \times 10^8 \text{ m/s}}{c}$$

$$\Delta p \geq 99 \frac{\text{MeV}}{c}$$

and the energy of the neutrino (a massless particle) is

$$E_\nu = |\mathbf{p}_\nu|c \geq 99 \text{ MeV}$$

Compared to the typical neutrino energy of 1 keV, this is much larger and thus the neutrino could not have come from inside the nucleus.

## Homework 2

Due 1/31

### 1. Muon Decay

The minimum energy of the electron would be equivalent to the rest mass

$$E_{\min} = m_e c^2 = 9.11 \times 10^{-31} \text{ kg} \cdot (3 \times 10^8 \text{ m/s})^2 = 8.2 \times 10^{-14} \text{ J} * \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}} = \boxed{0.512 \text{ MeV}}$$

The maximum energy of the electron would be when the electron moves in one direction and both neutrinos move together in the opposing direction. Thus we can treat this like a two body decay with the energy of the electron:

$$E_e = \frac{m_\mu^2 + m_e^2 - M^2}{2m_\mu} c^2$$

where  $M$  is the sum of the masses of the neutrinos  $M = 0$  (neutrinos are massless lol). Using the mass of the muon and electron:

$$m_e = 9.11 \times 10^{-31} \text{ kg} \cdot \frac{(3 \times 10^8 \text{ m/s})^2}{1.6 \times 10^{-19} \text{ J/eV}} = 0.51 \text{ MeV}$$

$$m_\mu = 1.88 \times 10^{-28} \text{ kg} = 106 \text{ MeV}$$

The maximum energy of the electron is then

$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} c^2 = \boxed{53 \text{ MeV}}$$

2. (a) For the head-on collision, we know that the initial energy is the sum of the rest masses of the protons and the minimum energy required to produce the antiproton. Thus

$$E_i = E_f$$

$$2m_p c^2 + E_{\min} = 4m_p c^2$$

$$E_{\min} = 2m_p c^2 = \boxed{1.88 \text{ GeV}}$$

(b) For the fixed target, we first look at the total momentum four vector before the collision: The zeroth component of the total momentum is

$$p^0 = \frac{E}{c} + \frac{E_{rest}}{c} = \frac{E}{c} + m_p c$$

thus the four-vector before the collision is

$$p^\mu = \left( \frac{E}{c} + m_p c, |\mathbf{p}| \right)$$

to find the four-vector after the collision, we can use the center of momentum frame (CM) where the two protons are viewed as going towards each other at the same speed like part (a), so the total three-vector momentum is zero. Thus the zeroth component of the four-vector is just the sum of the rest masses of the protons and the antiproton

$$p^{\mu'} = (4mc, 0)$$

we can then exploit the invariant dot product of the four-vectors to find the minimum energy

$$p^\mu p_\mu = p^{\mu'} p_{\mu'}$$

$$\left( \frac{E}{c} + m_p c \right)^2 - |\mathbf{p}|^2 = (4mc)^2$$





so from the first Mandelstoms variable

$$s = \frac{(p_A + p_B)^2}{c^2} = \frac{1}{c^2} \left[ \left( \frac{E_A}{c} + \frac{E_B}{c} \right)^2 + (\mathbf{p}_A + \mathbf{p}_B)^2 \right]$$

$$s = \frac{E_T^2}{c^4}$$

so

$$E_T = c^2 \sqrt{s}$$

(c) Since  $\mathbf{p}_A + \mathbf{p}_B = 0$  and  $E_A = E_B = E = \sqrt{\mathbf{p}^2 c^2 + m^2 c^4}$ , the Mandelstoms variable  $s$  is

$$\begin{aligned} \frac{1}{c^2} (p + p)^2 &= \frac{1}{c^2} \left[ \frac{(E_A + E_B)^2}{c^2} - (\mathbf{p}_A + \mathbf{p}_B)^2 \right] \\ &= \frac{1}{c^2} \left[ \frac{4E^2}{c^2} \right] \\ &= \frac{1}{c^2} \left[ \frac{\mathbf{p}^2 c^2 + m^2 c^4}{c^2} \right] \\ s &= \frac{\mathbf{p}^2 c^2 + m^2 c^4}{c^2} \end{aligned}$$

for  $t$  we assume the angle between  $\mathbf{p}_A$  and  $\mathbf{p}_C$  is  $\theta$  so

$$\begin{aligned} t &= \frac{1}{c^2} (p_A - p_C)^2 \\ &= \frac{1}{c^2} \left[ \left( \frac{E_A}{c} - \frac{E_C}{c} \right)^2 - (\mathbf{p}_A - \mathbf{p}_C)^2 \right] \end{aligned}$$

and we know that  $E_A = E_C$  so the first term is zero and the second term is

$$(\mathbf{p}_A - \mathbf{p}_C)^2 = \mathbf{p}_A^2 + \mathbf{p}_C^2 - 2\mathbf{p}_A \cdot \mathbf{p}_C$$

where  $\mathbf{p}_A^2 = \mathbf{p}_C^2 = \mathbf{p}^2$  and  $\mathbf{p}_A \cdot \mathbf{p}_C = \mathbf{p}^2 \cos \theta$  so

$$(\mathbf{p}_A - \mathbf{p}_C)^2 = 2\mathbf{p}^2 - \mathbf{p}^2 \cos \theta = 2\mathbf{p}^2 (1 - \cos \theta)$$

thus

$$t = \frac{1}{c^2} [0 - 2\mathbf{p}^2 (1 - \cos \theta)] = \frac{-2\mathbf{p}^2 (1 - \cos \theta)}{c^2}$$

for  $u$  everything is the same but  $\mathbf{p}_A \cdot \mathbf{p}_D = -\mathbf{p}^2 \cos \theta$  so

$$(\mathbf{p}_A - \mathbf{p}_D)^2 = 2\mathbf{p}^2 + \mathbf{p}^2 \cos \theta = 2\mathbf{p}^2 (1 + \cos \theta)$$

and thus

$$u = \frac{-2\mathbf{p}^2 (1 + \cos \theta)}{c^2}$$

4. First we know that the energy and momentum of a photon  $\gamma$  are

$$E_\gamma = h\nu = pc \quad p = \frac{h\nu}{c}$$

from the planck relation and energy-mass relation. Using conservation of energy we know that the before the collision it is the energy of the photon plus the rest mass of the electron:

$$\begin{aligned} E_i &= E_f \\ E_\gamma + m_e c^2 &= E'_\gamma + E_e \end{aligned}$$

and using the energy momentum relation for the electron

$$h\nu + m_e c^2 = h\nu' + \sqrt{p_e^2 c^2 + (m_e c^2)^2} \quad (1)$$

and from the conservation of momentum we know that

$$\mathbf{p} = \mathbf{p}' + \mathbf{p}_e \quad \text{or} \quad \mathbf{p}_e = \mathbf{p} - \mathbf{p}'$$

where the momentum of the electron is initially zero, squaring both sides

$$\begin{aligned} \mathbf{p}_e^2 &= (\mathbf{p} - \mathbf{p}')^2 \\ p_e^2 &= p^2 + p'^2 - 2\mathbf{p} \cdot \mathbf{p}' \end{aligned}$$

where we know that the dot product of the two momenta is

$$\mathbf{p} \cdot \mathbf{p}' = pp' \cos \theta$$

so

$$p_e^2 = p^2 + p'^2 - 2pp' \cos \theta \quad (2)$$

now we relate the two equations by first solving (1) for  $p_e^2 c^2$

$$p_e^2 c^2 = (h\nu^2 - h\nu'^2 + m_e c^2)^2 - (m_e c^2)^2$$

and then multiplying (2) by  $c^2$

$$p_e^2 c^2 = (pc)^2 + (p'c)^2 - 2pp'c^2 \cos \theta$$

and substituting the momentum of the photon from the energy relation  $p = \frac{h\nu}{c}$

$$p_e^2 c^2 = (h\nu)^2 + (h\nu')^2 - 2h^2 \nu \nu' \cos \theta$$

thus we can set the two equations equal to each other

$$\begin{aligned} (h\nu^2 - h\nu'^2 + m_e c^2)^2 - (m_e c^2)^2 &= (h\nu)^2 + (h\nu')^2 - 2h^2 \nu \nu' \cos \theta \\ (h\nu)^2 + (h\nu')^2 + (m_e c^2)^2 + 2(h^2 \nu \nu' - h\nu' m_e c^2 + h\nu m_e c^2) - (m_e c^2)^2 &= (h\nu)^2 + (h\nu')^2 - 2h^2 \nu \nu' \cos \theta \end{aligned}$$

where the first three terms cancel out

$$2(h^2 \nu \nu' - h\nu' m_e c^2 + h\nu m_e c^2) = -2h^2 \nu \nu' \cos \theta$$

dividing both sides by  $2h$  and rearranging terms gives

$$m_e c^2 (\nu - \nu') = h\nu \nu' (1 - \cos \theta)$$

dividing both sides again but by  $m_e c \nu \nu'$  gives

$$\left( \frac{c}{\nu'} - \frac{c}{\nu} \right) = \frac{h}{m_e c} (1 - \cos \theta)$$

and since the wavelength is  $\lambda = \frac{c}{\nu}$  we can solve for the outgoing wavelength

$$\lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \theta)$$

$$\boxed{\lambda' = \lambda + \frac{h}{m_e c} (1 - \cos \theta)}$$

## Homework 2

Due 2/7

### 1

(a) An electron has spin  $s = \frac{1}{2}$  so

$$j = \frac{3}{2}, \frac{1}{2}$$

for the 6 possible states of  $|j, j_z\rangle$ , the  $1 \otimes \frac{1}{2}$  C-B coefficients are

$$\begin{aligned} \left| \frac{3}{2}, \frac{3}{2} \right\rangle &= 1 \left| 1, \frac{1}{2} \right\rangle = |m_l, m_s\rangle \\ \left| \frac{3}{2}, \frac{1}{2} \right\rangle &= \frac{1}{\sqrt{3}} \left| 1, -\frac{1}{2} \right\rangle + \sqrt{\frac{2}{3}} \left| 0, \frac{1}{2} \right\rangle \\ \left| \frac{3}{2}, -\frac{1}{2} \right\rangle &= \sqrt{\frac{2}{3}} \left| 0, -\frac{1}{2} \right\rangle - \frac{1}{\sqrt{3}} \left| -1, \frac{1}{2} \right\rangle \\ \left| \frac{3}{2}, -\frac{3}{2} \right\rangle &= 1 \left| -1, -\frac{1}{2} \right\rangle \end{aligned}$$

and

$$\begin{aligned} \left| \frac{1}{2}, \frac{1}{2} \right\rangle &= \sqrt{\frac{2}{3}} \left| 1, -\frac{1}{2} \right\rangle - \frac{1}{\sqrt{3}} \left| 0, \frac{1}{2} \right\rangle \\ \left| \frac{1}{2}, -\frac{1}{2} \right\rangle &= \frac{1}{\sqrt{3}} \left| 0, -\frac{1}{2} \right\rangle + \sqrt{\frac{2}{3}} \left| -1, \frac{1}{2} \right\rangle \end{aligned}$$

(b) We can see for the  $|j = \frac{3}{2}, j_z = \frac{1}{2}\rangle$  state, the probability of measuring a spin  $s_z = \frac{1}{2}$  is proportional to the coefficient squared

$$P = \frac{2}{3}$$

### 2

(a) For the following processes

- The elastic processes are (from  $a \rightarrow f$ )

$$\pi^+ + p \rightarrow \pi^+ + p \quad (a)$$

$$\pi^0 + p \rightarrow \pi^0 + p \quad (b)$$

$$\pi^- + p \rightarrow \pi^- + p \quad (c)$$

$$\pi^+ + n \rightarrow \pi^+ + n \quad (d)$$

$$\pi^0 + n \rightarrow \pi^0 + n \quad (e)$$

$$\pi^- + n \rightarrow \pi^- + n \quad (f)$$

- The inelastic processes are (from  $g \rightarrow j$ )

$$\pi^+ + n \rightarrow \pi^0 + p \quad (g)$$

$$\pi^0 + p \rightarrow \pi^+ + n \quad (h)$$

$$\pi^- + p \rightarrow \pi^0 + n \quad (i)$$

$$\pi^0 + n \rightarrow \pi^- + p \quad (j)$$

The states are linear combinations of the states from Problem 1

$$\begin{aligned}
(a) & \rightarrow \left| 1, \frac{1}{2} \right\rangle = \left| \frac{3}{2}, \frac{3}{2} \right\rangle \\
(b) & \rightarrow \left| 0, \frac{1}{2} \right\rangle = \sqrt{\frac{2}{3}} \left| \frac{3}{2}, \frac{1}{2} \right\rangle - \frac{1}{\sqrt{3}} \left| \frac{1}{2}, \frac{1}{2} \right\rangle \\
(c) & \rightarrow \left| -1, \frac{1}{2} \right\rangle = \frac{1}{\sqrt{3}} \left| \frac{3}{2}, -\frac{1}{2} \right\rangle - \sqrt{\frac{2}{3}} \left| \frac{1}{2}, -\frac{1}{2} \right\rangle \\
(d) & \rightarrow \left| 1, -\frac{1}{2} \right\rangle = \frac{1}{\sqrt{3}} \left| \frac{3}{2}, \frac{1}{2} \right\rangle + \sqrt{\frac{2}{3}} \left| \frac{1}{2}, \frac{1}{2} \right\rangle \\
(e) & \rightarrow \left| 0, -\frac{1}{2} \right\rangle = \sqrt{\frac{2}{3}} \left| \frac{3}{2}, -\frac{1}{2} \right\rangle + \frac{1}{\sqrt{3}} \left| \frac{1}{2}, -\frac{1}{2} \right\rangle \\
(f) & \rightarrow \left| -1, -\frac{1}{2} \right\rangle = \left| -1, -\frac{1}{2} \right\rangle = \left| \frac{3}{2}, -\frac{3}{2} \right\rangle
\end{aligned}$$

Looking at the coefficients and the Isospin states, we can see the amplitudes as

$$\begin{aligned}
M_a &= M_f = M_3 \\
M_b &= M_e = \frac{2}{3}M_3 + \frac{1}{3}M_1 \\
M_c &= M_d = \frac{1}{3}M_3 + \frac{2}{3}M_1 \\
M_g &= M_h = M_i = M_j = \frac{\sqrt{2}}{3}(M_3 - M_1)
\end{aligned}$$

and the cross sections are proportional to the square of the amplitudes (coefficient square) or  $\sigma \propto |M|^2$ , but...

$$\begin{aligned}
\sigma_a : \sigma_c &= |M_3|^2 : \left| \frac{1}{3}M_3 + \frac{2}{3}M_1 \right|^2 \\
&= 9|M_3|^2 : |M_3 + 2M_1|^2
\end{aligned}$$

so the total ratios are

$$\begin{aligned}
&\sigma_a : \sigma_b : \sigma_c : \sigma_d : \sigma_e : \sigma_f : \sigma_g : \sigma_h : \sigma_i : \sigma_j = \\
&9|M_3|^2 : |2M_3 + M_1|^2 : |M_3 + 2M_1|^2 : |M_3 + 2M_1|^2 : |2M_3 + M_1|^2 \\
&: 9|M_3|^2 : 2|M_3 - M_1|^2 : 2|M_3 - M_1|^2 : 2|M_3 - M_1|^2 : 2|M_3 - M_1|^2
\end{aligned}$$

and for  $M_3 \gg M_1$  the ratios are

$$\boxed{9 : 4 : 1 : 1 : 4 : 9 : 2 : 2 : 2 : 2}$$

(b) For  $M_3 \ll M_1$  the ratios are

$$\boxed{0 : 1 : 4 : 4 : 1 : 0 : 2 : 2 : 2 : 2}$$

where (a) and (f) are very, very small cross sections in comparison.

### 3

(a) for protons  $I = \frac{1}{2}$  and neutrons,  $I = -\frac{1}{2}$  so the isospin of the  $\alpha$  particle is  $I = 0$ .

(b) On the LHS the isospin of the deuteron is  $I = 0$ , and on the RHS the isospin of the  $\alpha$  particle is  $I = 0$  so the isospin of the pion is  $I = 1$ . Since the isospin is not conserved  $0 \not\rightarrow 1$  the reaction is not allowed.

(c) The 4-proton state has isospin  $I = 2$  and this is *does not exist* since the isospin  $I = 1$  of the  ${}^4\text{Li}$  does not exist. The 4-neutron state with isospin  $I = -2$  *does not exist* as well due since the  ${}^4\text{H}$  isotope of  $I = -1$  does not exist. There can only be one possible 4-nucleon state:  ${}^4\text{He}$  with isospin  $I = 0$ .

## Homework 2

Due 2/14

1. (a) Imagining the electron as solid sphere, the moment of inertia is  $I = \frac{2}{5}m_e r^2$ . The speed at a point on its ‘equator’ is given by the tangential velocity  $v = \omega r \implies \omega = \frac{v}{r}$ . And if this electron is spinning with angular momentum  $\ell = \hbar/2$ , the speed of this point is

$$\begin{aligned}\ell &= I\omega \\ \frac{\hbar}{2} &= \frac{2}{5}m_e r^2 \frac{v}{r} \\ v &= \frac{5\hbar}{4m_e r}\end{aligned}$$

(b) If we have probed down to  $10^{-18}$  and still haven’t found any structure, then we would think that the radius of this electron solid sphere is  $r < 10^{-18}$ . Then the speed of the point on the equator is roughly

$$v > \frac{5 \times 10^{-34}}{4 \times 9 \times 10^{-31} \times 10^{-18}} \approx 10^{14} \text{ m/s}$$

which is much faster than the speed of light  $c = 3 \times 10^8$  m/s. So an electron is probably not spinning.

2. Given that the neutron, proton, and electron are all spin  $S = 1/2$  particles, the total spin of the beta decay

$$n \rightarrow p + e^-$$

on the left side is  $S_L = 1/2$  and on the right side we have  $S_R = \frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1$ . So the angular momentum is not conserved in this process. For the correct conservation of angular momentum, we need to include the neutrino in the decay

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

if we were to suppose the electron antineutrino had spin  $S = 1/2$ , then the total spin states could be  $1/2$  or  $3/2$  and the angular momentum would be conserved. We could also suppose it has spin  $S = 3/2$  and the possible total spin states could be  $1/2, 3/2$  or,  $5/2$  which also conserves angular momentum. This means that any half integer spin would conserve angular momentum in the beta decay.

3. If the  $J_i$ ’s are Hermitian, then

$$J_i^\dagger = J_i, \quad J_j^\dagger = J_j, \quad J_k^\dagger = J_k$$

and the commutator is defined as

$$[J_i, J_j] = J_i J_j - J_j J_i$$

taking the Hermitian conjugate of the commutator

$$\begin{aligned}[J_i, J_j]^\dagger &= (J_i J_j - J_j J_i)^\dagger \\ &= (J_i J_j)^\dagger - (J_j J_i)^\dagger \\ &= J_j^\dagger J_i^\dagger - J_i^\dagger J_j^\dagger \\ &= J_j J_i - J_i J_j \\ &= -(J_i J_j - J_j J_i) = -[J_i, J_j]\end{aligned}$$

where on the 3rd step we know that the Hermitian adjoint (conjugate *transpose*) of a product of matrices is the product of the Hermitian adjoints in reverse order i.e.  $(AB)^\dagger = B^\dagger A^\dagger$  because transposes do this. taking the Hermitian adjoint of the right hand side:

$$(if_{ijk} J_k)^\dagger = -if_{ijk}^\dagger J_k$$

so

$$-[J_i, J_j] = -i f_{ijk}^\dagger J_k \rightarrow [J_i, J_j] = i f_{ijk}^\dagger J_k$$

and in order for the commutator relation to be true, the structure constants must be real i.e.  $f_{ijk} = f_{ijk}^\dagger$  (real numbers are Hermitian).

4.  $f$  as a sum:

$$f(x, y, z) = f_+(x, y, z) + f_-(x, y, z)$$

Parities are:

$$P(f_+) = +f_+, \quad P(f_-) = -f_-, \quad P(f(x, y, z)) = f(-x, -y, -z)$$

where the parity of  $f$  is just the inversion(reflection + 180 degree rotation). Thus the parity of the RHS:

$$\begin{aligned} P(f(x, y, z)) &= P(f_+(x, y, z)) + P(f_-(x, y, z)) \\ f(-x, -y, z) &= (+f_+(x, y, z)) + (-f_-(x, y, z)) \end{aligned}$$

solving for  $f_+$  and substituting  $f_- = f - f_+$ :

$$\begin{aligned} f_+(x, y, z) &= f(-x, -y, z) + f_-(x, y, z) \\ &= f(-x, -y, z) + f(x, y, z) - f_+(x, y, z) \\ 2f_+(x, y, z) &= f(-x, -y, z) + f(x, y, z) \\ f_+(x, y, z) &= \frac{1}{2}(f(x, y, z) + f(-x, -y, z)) \end{aligned}$$

and similarly by substituting the result back into  $f_- = f - f_+$ :

$$f_-(x, y, z) = \frac{1}{2}(f(x, y, z) - f(-x, -y, z))$$

we can see that

$$f_+(x, y, z) + f_-(x, y, z) = f(x, y, z)$$

where  $f_+$  and  $f_-$  is an eigenfunction of the parity operator with eigenvalues +1 and -1 respectively.

5. (a) Given that for EM & Strong interactions, the parity must be conserved. For the decay

$$\eta \rightarrow 2\pi$$

the parity of  $\eta$  is  $P(\eta) = -1$  and the parity of  $2\pi$  is  $P_{tot} = (P(\pi))^2 = (-1)^2 = 1$ . So the parity is not conserved in this decay and thus forbidden for EM & Strong interactions.

(b) For the decay

$$\eta \rightarrow 3\pi$$

we can see that the parity is conserved:  $P(\eta) = P_{tot} = (P(\pi))^3 = -1$ . Since a G-parity violation forbids decay under Strong interactions, the G-parity of the two sides are:

$$G(\eta) = (-1)^0 C = 1(+1) = +1, \quad G(3\pi) = (-1)^3 = -1$$

so G-parity conservation is violated and the decay is forbidden under Strong interactions, but allowed for EM interactions due to Parity conservation.