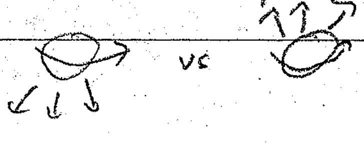
Fundamental Discrete Symmetries

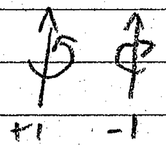
– Parity = Reflection symmetry

- Parity P is reflection of all coordinates $P(\vec{x}) = -\vec{x}$
  - + Acting twice gives identity $P^2 = \mathbb{1}$
    - $\Rightarrow$ the group is $\mathbb{Z}_2 = \{1, P\}$
  - + Eigenvalues for acting on physical quantities are ± 1
  - + Reflection acts on all particles, so e'values multiply $P(|a\rangle|b\rangle) = (P|a\rangle)(P|b\rangle)$
- Types of physical quantities (eigenstates of P)
  - + Scalars unchanged by rotations and have $P = +1$
    - Example is a dot product $\vec{x} \cdot \vec{y}$
  - + Vectors rotate like position and have $P = -1$
    - Example is position vector $\vec{x}$ or electric field $\vec{E}$
  - + Pseudovectors (aka axial vector) rotate like vectors but have $P = +1$
    - Example is a cross product $(\vec{x} \times \vec{y})$
  - + That means there are pseudoscalars like $\vec{x} \cdot (\vec{y} \times \vec{z})$ unchanged by rotations but with $P = -1$

- Particles can fall in those categories
  - + Photons are vectors
  - + Mesons are vectors or pseudoscalars
  - + You can look up P e'values in RPP
- Strong + electromagnetic interactions conserve parity. Weak interactions violate parity
  - + Wu's experiment: Co-60 has beta decay, meaning it emits an electron. Electrons always come out opposite the nuclear spin (She did not get the Nobel, controversial)
  - + Why does this violate parity? momentum is a vector, angular momentum is pseudovector, so parity reverses their alignment.

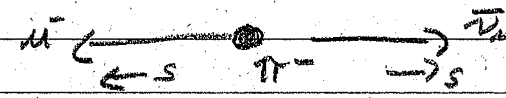


- Handedness and the weak force
  + Helicity of a particle is about its spin alignment: for a spin-$\frac{1}{2}$ particle, define momentum to be along z-axis. Then $m_s = +\frac{1}{2}$ (aligned w/ $\vec{p}$) is helicity +1 ; $m_s = -\frac{1}{2}$ (antialigned) is helicity −1



  + Helicity is connected to a technical concept of handedness
    +1 ≈ right handed, −1 ≈ left-handed.

  + The weak force interacts only with LH neutrinos and RH antineutrinos
  + Interacts w/ ang. mom. conservation: consider $\pi^- \to \mu^- + \bar{\nu}_\mu$. π^- is scalar (spin 0). Since $\bar{\nu}_\mu$ is RH, μ^- must be RH for ang. mom.



    Similar to Wu expt.

- + Are there RH neutrinos? If a particle moves at less than c, there is a reference frame where it is moving in the other direction, which reverses helicity. We know ν have a small mass ⟹ suggests RH ν.

- Weak-force-induced particle decays violate parity
  + Example: K^+ has $P = -1$. It can decay to $\pi^+\pi^0\pi^0$ or $\pi^+\pi^+\pi^-$ also $P=-1$ or $\pi^+\pi^0$ $P=+1$
  + Remember that parity eigenvalues multiply for multiple particles

— Charge Conjugation
- This is the symmetry that switches particles + antiparticles
  + Like parity, $C^2 = 1$, Group is Z_2. Means eigenvalues are ±1
  + Eigenstates are only particles that are their own antiparticles

+ Eigenvalues multiply, like for parity

- C reverses electric charge, so only neutral particles can be eigenstates
  + Reversing charge reverses field + potential ⟹ photons have $C = -1$
  + But that's not enough: neutrons ≠ antineutrons due to constituent quarks
  + Some neutral mesons are C eigenstates, like π^0 has $C = +1$
  + There is a generalization called G that includes sets of mesons like (π^+, π^0, π^-)

- EM + strong force respect C, but not weak. (Why?)

- CP = combination of C + P
  + Changes LH $\nu \to$ RH $\bar{\nu}$. Maybe weak respects CP?

  + Oddly, neutral kaons can oscillate $K^0 \leftrightarrow \bar{K}^0$
  a) So we might consider CP eigenstates
  $K_1 = (|K^0\rangle - |\bar{K}^0\rangle)/\sqrt{2}$, $K_2 = (|K^0\rangle + |\bar{K}^0\rangle)/\sqrt{2}$
  with $CP|K_1\rangle = |K_1\rangle$ and $CP|K_2\rangle = -|K_2\rangle$
  b) Kaons normally produced by strong force as K^0 or $\bar{K}^0$
  But decay weakly as K_1 or K_2
  c) If CP is a symmetry, decays are
  $K_1 \to \pi\pi$ $(CP = +1)$, $K_2 \to \pi\pi\pi$ $(CP = -1)$
  K_1 decays faster b/c it releases more kinetic energy

- CP violation
  + Think about the neutral kaons some more. After travelling far enough, only K_2 is left
  + However, it turns out that there are still a few decays to $\pi\pi$! That means the long-lived K is not actually K_2 but
  $|K_L\rangle \approx |K_2\rangle + \epsilon|K_1\rangle$ for $\epsilon \ll 1$

  + Originates in weak interaction of quarks + shows up in other meson systems.

- CP violation puzzles
  + Why doesn't strong violate CP? Proposed answers, not experimentally confirmed
  + CP violation gives a difference between matter and antimatter. How does this play into the predominance of matter in the universe?

- Time Reversal
  - T symmetry means any process runs at the same rate backwards as forwards
    + It's very hard to test in this way
    + However, a static electric dipole moment of a particle violates T (the dipole must align with spin, but spin reverses direction when time reverses)
    + There are numerous expts. to measure e^- and n EDM
  - CPT theorem
    + There is a theorem for any relativistic quantum field theory that the combination of CPT must be conserved
    + So T must be violated in weak interactions
    + CPT means mass + lifetime of particle + antiparticle must be equal
    + Ongoing expts to test, but violation would be crazy!