PHY492: Nuclear & Particle Physics

Lecture 15

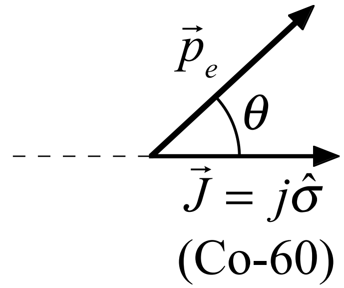
Symmetries III

Neutral K-mesons & CP Violation

Parity violation in weak interactions

- Parity violated in weak interactions
  - Beta decay of polarized Co-60

$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$



Rate vs. angle must be a scalar function

Only scalar using the vector variables is

$$\hat{\sigma} \bullet \vec{p}$$

(pseudo)scalar combination of vector quantities

Most general linear form

$$I(\theta) = 1 + \alpha\left(\frac{\hat{\sigma} \bullet \vec{p}c}{E}\right)$$

$$= 1 + \alpha\beta\cos\theta$$

$\hat{\sigma}$ is "axial" vector $(\hat{r} \times \hat{q})$

$$P(\hat{\sigma}) = +\hat{\sigma}; \quad P(\vec{p}) = -\vec{p}$$

$$P(\hat{\sigma} \cdot \vec{p}) = -\hat{\sigma} \cdot \vec{p}$$

Any angular asymmetry is reversed in a parity inverted world.

If parity is conserved the angular dependence must be symmetric w.r.t. spin

Strong angular asymmetry seen ---> Parity Violated

Tau-Theta puzzle resolved

- Two particles same mass and decay lifetime, and spin = 0.
- Only difference: one was negative parity, the other positive parity.

$$\tau^+ \to \pi^+ + \pi^0$$
$$\theta^+ \to \pi^+ + \pi^+ + \pi^-$$

$$P\left(\tau^+\right) = P\left(\pi^+\right)P\left(\pi^0\right) = +1$$
$$P\left(\theta^+\right) = P^2\left(\pi^+\right)P\left(\pi^-\right) = -1$$

- This led Lee and Yang to propose that parity might be violated in weak interactions ---> particle is K^+ with two decay modes.
- Stimulated Wu's experiment (previous slide) with ^{60}Co
- Stimulated Lederman's experiment with muon decay
  - polarized muons produced in pi-meson decay
  - Polarized muons stopped in carbon block (kept polarization)
  - Observe direction of positrons w.r.t. muon polarization

$$\frac{dN}{d\Omega} = 1 - \frac{\alpha}{3}\cos\theta$$

angular dependence is asymmetric
parity violated in muon decay.

Time reversal invariance

- Newtonian mechanics is invariant to t --> -t.
- Maxwell's Equations are invariant to t --> -t.
- Quantum mechanical wave functions almost invariant

$$\psi(\vec{r},t) \xrightarrow{T} \psi^*(\vec{r},-t)$$

Probability $= \psi^* \psi$ is invariant

- An electric dipole moment of the neutron would violate T.

$$\vec{s} \xrightarrow{T} -\vec{s}$$
$$\vec{\mu}_E \xrightarrow{T} \vec{\mu}_E$$

$$\vec{\mu}_E \cdot \vec{s} \xrightarrow{T} -\vec{\mu}_E \cdot \vec{s}$$

- Maximum expectation is qr with q~e, and r~10^{-13}cm: $\mu_E \sim 10^{-13}$ e-cm

Experimental limit

$$\mu_E < 10^{-25} \text{ e-cm}$$

Charge conjugation

- Charge conjugation operator (*C*) makes particle <---> anti-particle
- All charges (electric charge, lepton #, baryon #, etc.,) must be zero for particle to be eigenstate of *C* operator.
- Photon has *C*-parity = –1
- Neutral pion ($\pi^0 \to \gamma+\gamma$)
  - *C*-parity = +1
  - No π^0 decays to odd number of photons
- *C*-parity is conserved in strong and electromagnetic interactions
- *C*-parity is violated in weak interactions
  - Only left-handed neutrinos and right-handed anti-neutrinos exist.
  - *C*(left-handed neutrino) --> left-handed anti-neutrino (but none exist)
- Combination of *C* & P is symmetry of weak interaction (*ALMOST*)
  - CP(left-handed neutrino) --> right-handed anti-neutrinos (OK)
  - CP(right-handed anti-neutrinos) --> left-handed neutrino (OK)
  - K^0 system violates even this CP symmetry

Review of symmetries

- Nother's theorem: symmetry <----> conserved/invariant quantity
- Continuous symmetries of space and time
  - Conserved: Momentum & Energy, Angular momentum, Charge
  - Symmetry: shifts in space & time, rotations, gauge transformations
- Discrete symmetries of all interactions (strong, weak, EM)
  - Baryon # (B), Lepton # (|Q|=1, 0) (n_e,n_μ,n_τ), Color (quark, gluon)
- Discrete symmetries violated by weak interactions
  - Isospin (I, I_3): $\Delta I = 1/2$ "rule" (Isospin also violated by EM interactions)
  - Quark flavor (u,d,s,c,b,t): changed in "charged current" interactions
  - Parity, $P\Psi(x_i) \neq (+/-)\Psi(x_i)$; Particle parity not maintained in weak decays
  - Charge Conjugation [C (particle) = anti-particle] not maintained in decays
- Discrete symmetry of Time reversal (T) invariance
  - looks good, but must be violated
- NOTE: CPT theorem: $CPT\Psi(x_i) = \Psi(x_i)$ ABSOLUTE(locality/causality)

K^0 & $\overline{K^0}$ mixing

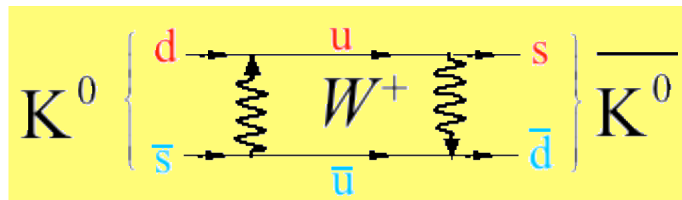
- Parity violation in K^+ decay
  - 2 pions, P = +
  - 3 pions, P = -
  - T.D. Lee, C.N. Yang (1956)

$$K^+ \to \pi^+\pi^0 \text{ or } \pi^+\pi^+\pi^- \quad (\tau = 1.2\times 10^{-8}\text{s})$$

$(\tau^+,\ \theta^+$ puzzle)

- Prediction for K^0 decays
  - M. Gell-Mann & A. Pais (1955)
  - Two decay constants
  - CP eigenstates are the key
  - Weak Interaction (2nd order) can cause particle ---> antiparticle for neutral particles

$$K^0 \to \pi^+\pi^- \quad (\tau = 0.9\times 10^{-10}\text{s}) \text{ fast}$$
$$K^0 \to \pi^+\pi^-\pi^0 \quad (\tau = 0.5\times 10^{-7}\text{s}) \text{ slow}$$



- K^0 is not an eigenstate of C or P.
- linear combinations are eigenstates of CP

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

K^0 & $\bar{K}^0$ oscillations

- Neutral K decays
  - $\pi^+\pi^-$, P = +1, C = +1, CP = +1
  - $\pi^+\pi^-\pi^0$, P = −1, C = +1, CP = −1

$$\left|K_1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right) \quad \text{fast decay}$$

$$\left|K_2\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right) \quad \text{slow decay}$$

Invert

- K^0 & $\bar{K}^0$ created by strong interactions.
  - weak interactions select K_1 & K_2 and have slightly different masses ($\Delta m = m_2 - m_1$)
  - Mix of K_1 and K_2 will change as particle propagates
  - time dependence almost straight from QM text book.

$$\left|K^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K_1\right\rangle + \left|K_2\right\rangle\right)$$

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

$$\left|K_1(t)\right\rangle = K_1(0)\left[e^{im_1c^2t/\hbar}e^{-\Gamma_1 t/2\hbar}\right]$$

$$\left|K_2(t)\right\rangle = K_2(0)\left[e^{im_2c^2t/\hbar}e^{-\Gamma_2 t/2\hbar}\right]$$

- Starting with pure K^0, the $\bar{K}^0$ intensity grows then oscillates

$$I\left(\bar{K}^0\right) = \tfrac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-[(\Gamma_1+\Gamma_2)/2]t}\cos\left(\Delta mc^2 t/\hbar\right)\right]$$

$$\tau = 2\pi\hbar / \Delta mc^2 = 1.2\times10^{-9}\,\text{s}$$

$$\Delta mc^2 = 3.52\times10^{-6}\ \text{eV}$$

K_1 regeneration

- Far from production point K^0 beam will be pure K_2 (all K_1 decayed)

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \text{ slow decay}$$

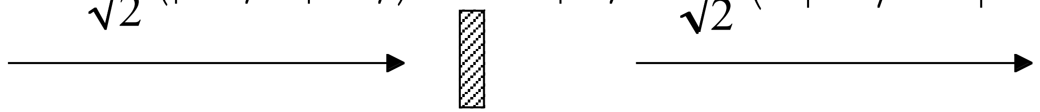
- Neutral K interactions
  - s-quark is in strange baryons
  - $\bar{K}^0$ preferentially removed from beam

$$\begin{array}{ccccc} \bar{K}^0 + p & \rightarrow & \pi^+ + \Lambda^0 \\ (s\,\bar{d}) + (uud) & \rightarrow & (u\,\bar{d}) + (sud) \end{array}$$

$$\sigma_{\bar{K}^0} > \sigma_{K^0}$$

<u>Send K_2 beam into a thin target</u>

$$|K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad |\psi\rangle = \frac{1}{\sqrt{2}}\left(f|K^0\rangle + \bar{f}|\bar{K}^0\rangle\right); \quad f > \bar{f}$$



$$|\psi\rangle = \tfrac{1}{2}(f+\bar{f})|K_2\rangle + \tfrac{1}{2}(f-\bar{f})|K_1\rangle$$
$$\langle K_1|\psi\rangle = \tfrac{1}{2}(f-\bar{f}) \neq 0$$

- "Regenerate" K_1 -->π^++π^- decays near the target

CP violation in K decays

- 1964 Christenson, Cronin, Fitch, & Turlay discover ~3x10^{-3} of K_2 beam decays to $\pi^+ + \pi^-$ or $\pi^0 + \pi^0$

K^0 and K^0-bar are not pure mixtures of K_1 & K_2 CP eigenstates

- Short lived version is called K_S^0 and long lived called K_L^0

  K_L^0 = mostly K_2 with a little K_1, so causes "indirect" CP violation

$$\left|K_L^0\right\rangle = \frac{1}{\sqrt{1+\left|\varepsilon\right|^2}}\left(\left|\mathrm{K}_2\right\rangle + \varepsilon\left|\mathrm{K}_1\right\rangle\right)$$

- Also H_{weak} has a very small direct CP violating term

  - Parity violation in weak interactions is maximal.

    No right handed neutrinos have ever been found.

    Relativistic quantum mechanics can handle this well.

  - CP violation is a whole other story, that continues to dominate about 1/2 of all HEP to this day.

What's all the fuss about CP violation?

- Semi-leptonic decays of K_L^0 :

$$\left|K_L\right\rangle \rightarrow \pi^+ + e^- + \bar{\nu}_e$$
$$\left|K_L\right\rangle \rightarrow \pi^- + e^+ + \nu_e$$

- If CP were a good symmetry decays should be identical (decay fraction, etc.)

- Experiments show the e^+ decay greater than e^- decay by 3.3 parts in 1000, -> CP violation.

Consequences of CP violation

1. Makes absolute distinction of matter (e^-) from anti-matter (e^+).
2. Provides unambiguous definition of "positive" charge.
3. Since CPT is good symmetry, CP violation implies Time reversal symmetry (T) is also broken - though never seen.
4. May be responsible for matter-antimatter asymmetry in nature.