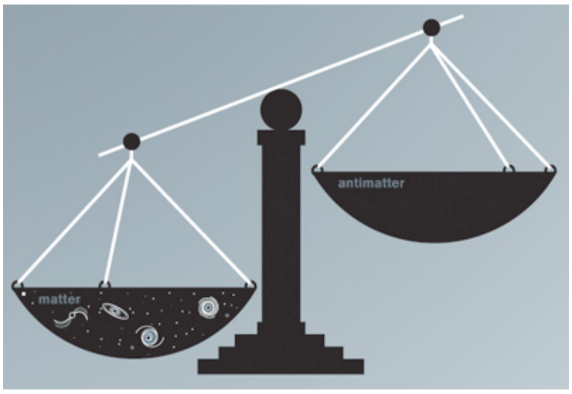
Particle Physics

Dr Victoria Martin, Spring Semester 2012
Lecture 14: ***CP*** and ***CP*** Violation



★Parity Violation in Weak Decay
★***CP*** and ***CPT***
★Neutral meson mixing
★Mixing and decays of kaons
★***CP*** violation in $\mathbf{K^0}$ and $\mathbf{B^0}$

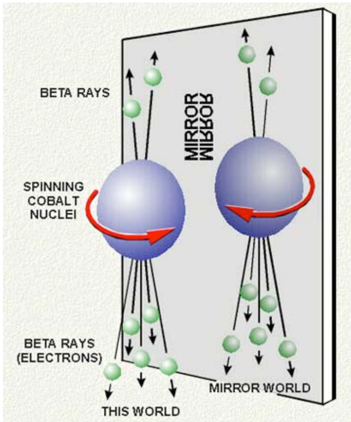
Summary from Tuesday

- Symmetries play a key role in describing interactions in particle physics.
- QED and QCD obey Gauge symmetries in the Lagrangian corresponding to symmetry groups. These lead to conservation of electric and colour charge.
- Three important discreet symmetries: Charge Conjugation (C), Parity (P) and Time reversal (T).
  - C: changes the sign of the charge
  - P: spatial inversion, reverses helicity. Fermions have $P=+1$, antifermions $P=-1$
  - T: changes the initial and final states
  - Gluons and photons have $C=-1$, $P=-1$

- C and P are conserved in QED and QCD, maximally violated in weak
- Only LH neutrinos and RH anti-neutrinos are found in nature.

- CPT is thought to be absolutely conserved (otherwise RQFT doesn't work!)

Parity Violation in Weak Decays



- First observed by Chien-Shiung Wu in 1957 through β-decay of polarised ^{60}Co nuclei: $^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$
  - Recall: under parity momentum changes sign but not nuclear spin
- Electrons were observed to be emitted to opposite to nuclear spin direction
- Particular direction is space is preferred!

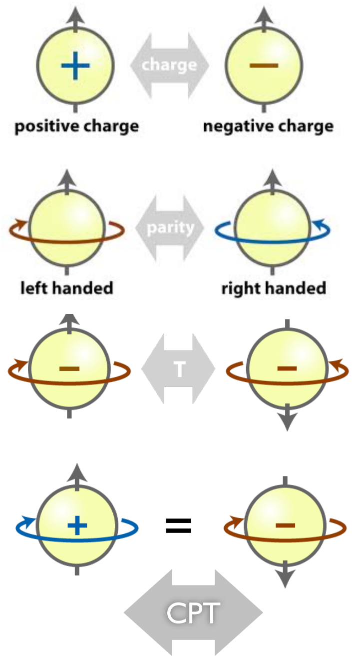
- P is found to be violated maximally in weak decays
- Still a good symmetry in strong and QED.

- Recall the vertex term for the weak force is $g_w\, \gamma^\mu(1-\gamma^5)/\sqrt{8}$
- Fermion currents are proportional to $\bar{\psi}(e)\, (\gamma^\mu - \gamma^\mu\gamma^5)\, \psi(\nu_\mu)$ **"vector – axial vector"**
- Under parity, $P\,(\bar{\psi}\, (\gamma^\mu - \gamma^\mu\gamma^5)\, \psi) = \bar{\psi}\, (\gamma^\mu + \gamma^\mu\gamma^5)\, \psi$ (mixture of eigenstates)

- Compare to QED and QCD vertices: $P\,(\bar{\psi}\, \gamma^\mu\, \psi) = \bar{\psi}\, \gamma^\mu\, \psi$

(pure eigenstates - no P violation)

CPT Theorem



- ***CPT*** is the combination of ***C, P*** and ***T***.
  Turns a forward-going particle with LH helicity into backward-going antiparticle with RH helicity.
- ***CPT*** Theorem states:

  "All interactions described by a local Lorentz invariant gauge theory must be invariant under the combined operation ***CPT***"

  ➡ ***CPT*** violation would imply non-locality and/or loss of Lorentz invariance

  ➡ Impossible to write down relativistic quantum field theories?

  ➡ Impossible to describe interactions in terms of Feynman diagrams?

  ➡ ***CPT*** conservation implies that ***CP*** violation is equivalent to ***T*** violation

- The Universe needs ***CP*** violation for the matter-antimatter asymmetry and it needs ***T*** violation for the arrow of time

Tests of *CPT* Invariance

- ***CPT*** invariance implies particles and antiparticles must have equal masses:

$$\frac{M(\mathrm{K}^0) - M(\overline{\mathrm{K}}^0)}{\frac{1}{2}[M(\mathrm{K}^0) + M(\overline{\mathrm{K}}^0)]} < 10^{-18}$$

- Particle and antiparticles must have equal lifetimes:

$$\frac{\Gamma(\mathrm{K}^0) - \Gamma(\overline{\mathrm{K}}^0)}{\frac{1}{2}[M(\mathrm{K}^0) + M(\overline{\mathrm{K}}^0)]} < \times 10^{-17}$$

Don't learn all these limits, just for your appreciation

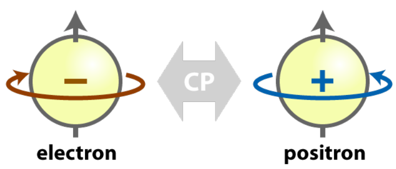
- Particle and antiparticles must have equal and opposite charges and magnetic moments

$$Q(p) + Q(\bar{p}) < 10^{-21} e \qquad \frac{g(e^+) - g(e^-)}{\frac{1}{2}[g(e^+) + g(e^-)]} < 2 \times 10^{-12}$$

- Hydrogen and anti-hydrogen atoms have identical spectra

CP Symmetry

- ***C*** is also found to be maximally violated in weak decays.
- Experimental results suggest the combination ***CP*** is a conserved symmetry.
- ***CP*** turns a particle into its antiparticle with opposite helicity: it is a symmetry between matter and anti-matter



- ***CP*** is a conserved quantity in strong and electromagentic interactions.
- It is ***nearly*** a conserved quantity in weak interactions, but not quite.
- Violation of ***CP*** symmetry is required to explain the different between the matter and anti-matter content of the universe.

- We will see that ***CP*** comes about due to a complex phase in the CKM matrix.

LHCb and the Matter-Antimatter Asymmetry

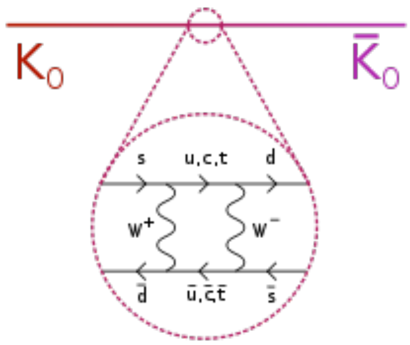
- http://www.youtube.com/watch?v=EVQnjuCej6I&feature=related

Neutral Meson Mixing

- Second order weak interactions can mix long-lived neutral mesons with their antiparticles:
  - ➡ $\mathbf{K^0\,(\bar{s}\,d\,),\ D^0\,(\bar{c}\,u\,),\ B^0\,(\bar{b}\,d),\ B_s\,(\bar{b}\,s)}$ $\quad \mathbf{K^0 \leftrightarrow \overline{K}^0\ \ D^0 \leftrightarrow \overline{D}^0\ \ B^0 \leftrightarrow \overline{B}^0\ \ B_s \leftrightarrow \overline{B}_s}$
- e.g. take the neutral kaons $\mathbf{K^0}$ $\mathbf{\overline{K}^0}$ as an example:

$$P\,|\mathrm{K}^0\rangle = -|\mathrm{K}^0\rangle \qquad P\,|\overline{\mathrm{K}}^0\rangle = -|\overline{\mathrm{K}}^0\rangle$$

$$CP\,|\mathrm{K}^0\rangle = -|\overline{\mathrm{K}}^0\rangle \qquad CP\,|\overline{\mathrm{K}}^0\rangle = -|\mathrm{K}^0\rangle$$



- The CP eigenstates are:

$$|\mathrm{K}_1\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle - |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = +1$$

$$|\mathrm{K}_2\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle + |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = -1$$

- Decay eigenstates are (approximately) $\mathbf{K_1}$ and $\mathbf{K_2}$ - **not** the same as the flavour eigenstates $\mathbf{K^0}$ and $\mathbf{\overline{K}^0}$
- Two common decay modes are $\mathbf{2\pi}$ and $\mathbf{3\pi}$
  - $\pi^0\pi^0$ and $\pi^+\pi^-$ have $CP = +1$
  - $\pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ have $CP = -1$

Neutral Kaons continued

- ***CP*** is almost conserved in the decay of the neutral kaons.
- Decay $\mathbf{K \to \pi\pi}$ has large phase space ⇒ quick decay, travels ~ cm before decay
  - named "**K**-short" or $\mathbf{K_S}$ with $\boldsymbol{\tau_S = 0.09}$ **ns**
- Decay $\mathbf{K \to \pi\pi\pi}$ has small phase space ⇒ slow decay, travels ~ 10 m before decay
  - "**K**-long" or $\mathbf{K_L}$ with $\boldsymbol{\tau_L = 51}$ **ns**

- After a neutral kaon is produced, at some time, ***t***, later it will be described by:

$$\psi(t) = a(t)|\mathrm{K}^0\rangle + b(t)|\overline{\mathrm{K}}^0\rangle$$

- The evolution of the kaon state described by mass & decay matrices: **M, Γ**

$$i\frac{\partial\psi(t)}{\partial t} = \hat{H}\psi(t) = (\hat{M} - \frac{i}{2}\hat{\Gamma})\psi(t)$$

$$\hat{M} - \frac{i}{2}\hat{\Gamma} = \begin{pmatrix} M_\mathrm{K} - \frac{i}{2}\Gamma_\mathrm{K} & \Delta m_\mathrm{K} - \frac{i}{2}\Delta\Gamma_\mathrm{K} \\ (\Delta m_\mathrm{K})^* - \frac{i}{2}(\Delta\Gamma_\mathrm{K})^* & M_\mathrm{K} - \frac{i}{2}\Gamma_\mathrm{K} \end{pmatrix}$$

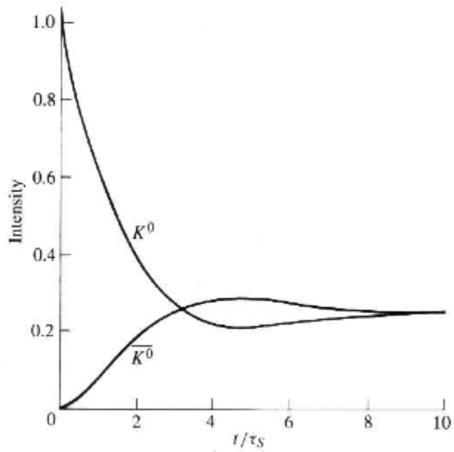
- Mass difference $\boldsymbol{\Delta m_\mathrm{K} = m_S - m_L = 3.52(1) \times 10^{-12}}$ **MeV** $\boldsymbol{= 0.53 \times 10^{-10}\ \mathrm{s}^{-1}}$ is oscillation frequency

Time Evolution of $\mathbf{K^0}$

- The time evolution of the $\mathbf{K_S}$ and $\mathbf{K_L}$ states are:

$$\mathrm{K_S}(t) = \mathrm{K_S}(0)\exp\{-(\Gamma_\mathrm{S}/2 + im_\mathrm{S})t\}$$

$$\mathrm{K_L}(t) = \mathrm{K_L}(0)\exp\{-(\Gamma_\mathrm{L}/2 + im_\mathrm{L})t\}$$



- In terms of the weak (or flavour) eigenstates:

$$\mathrm{K}^0(t) = \frac{1}{4}\left[e^{-\Gamma_\mathrm{L}t} + e^{-\Gamma_\mathrm{S}t} + 2e^{-\Gamma t}\cos\Delta m_\mathrm{K}t\right]$$

$$\overline{\mathrm{K}}^0(t) = \frac{1}{4}\left[e^{-\Gamma_\mathrm{L}t} + e^{-\Gamma_\mathrm{S}t} - 2e^{-\Gamma t}\cos\Delta m_\mathrm{K}t\right]$$

  - where $\boldsymbol{\Gamma = \frac{1}{2}(\Gamma_S + \Gamma_L)}$

- If you start with beam of neutral kaon (either $\mathbf{K^0}$, $\mathbf{\overline{K}^0}$ or a mixture) it will end up a beam of almost pure $\mathbf{K_L}$

Neutral Kaons with *CP* Violation

- The *CP* eigenstates are $\mathbf{K_1}$ and $\mathbf{K_2}$

$$|\mathrm{K}_1\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle - |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = +1$$

$$|\mathrm{K}_2\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle + |\overline{\mathrm{K}}^0\rangle\right) \qquad CP = -1$$

- The decay $\mathbf{K_S}$ and $\mathbf{K_L}$ are not quite the same as the decay eigenstates, instead in terms of a small parameter $\boldsymbol{\varepsilon}$:

$$|\mathrm{K_S}\rangle = \frac{1}{N}\left((1-\epsilon)|\mathrm{K}^0\rangle - (1+\epsilon)|\overline{\mathrm{K}}^0\rangle\right)$$

$$|\mathrm{K_L}\rangle = \frac{1}{N}\left((1+\epsilon)|\mathrm{K}^0\rangle + (1-\epsilon)|\overline{\mathrm{K}}^0\rangle\right)$$

- The decay states contain both $\boldsymbol{CP = +1}$ and $\boldsymbol{CP = -1}$, ***CP*** is violated.

$$|\mathrm{K_S}\rangle = \frac{1}{N}\left(|\mathrm{K}_1\rangle - \epsilon|\mathrm{K}_2\rangle\right)$$

$$|\mathrm{K_L}\rangle = \frac{1}{N}\left(|\mathrm{K}_2\rangle + \epsilon|\mathrm{K}_1\rangle\right)$$

- $\boldsymbol{\varepsilon}$ is measured to be $|\boldsymbol{\varepsilon}| \sim \mathbf{2 \times 10^{-3}}$, the amount of **indirect *CP* violation** due to mixing of different *CP* eigenstates $\mathbf{K_1}$ and $\mathbf{K_2}$

Summary

- Parity *P* and Charge Conjugation *C* are maximally violated in weak interactions due to vector – axial vector structure of interaction vertex.
  - Conserved in strong and electromagnetic interactions.
- The combined symmetry *CP* describes the difference between matter and anti-matter
  - almost a good symmetry in the weak interactions.
- *CPT* symmetry must be conserved… it's one of the foundations of QM and field theory!
- Small amounts of *CP* violation observed in $\mathbf{K^0}$ and $\mathbf{B^0}$ decays and mixing.
  - (New this year also in charm-mesons: $\mathbf{D^0}$)
- Three types of *CP* violation:
  1. Direct *CP* violation in decay amplitudes
  2. *CP* violation in neutral meson mixing
  3. Indirect *CP* violation due to interference of mixing and decay.
- The amount of *CP* observed is not enough to explain the matter – anti-matter asymmetry of the universe.