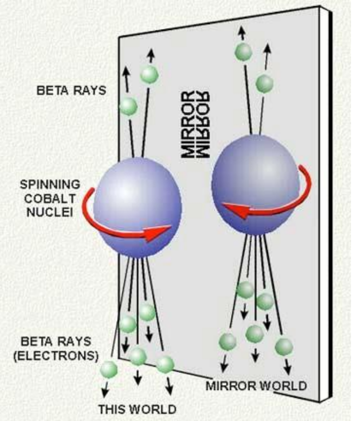
Particle Physics

Parity Violation in Weak Decays



- First observed by Chien-Shiung Wu in 1957 through !decay of polarised ^{60}Co nuclei: $^{60}\mathrm{Co}\,''\,^{60}\mathrm{Ni} + e^{\#} + \$_{e}$ • 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 $g_{w}\ \text{"}^{\mu}(1!\text{"}^{5})\ /\#8$

- Fermion currents are proportional to $\$(e)\ (\text{"}^{\mu}!\text{"}^{\mu}\text{"}^{5})\ \$(\%_{\mu})$ **“vector ! axial vector”**

- Under parity, $P\,(\$\ (\text{"}^{\mu}\,!\ \text{"}^{\mu}\text{"}^{5})\ \$)\ =\ \$\ (\text{"}^{\mu} + \text{"}^{\mu}\text{"}^{5})\ \$$ (mixture of eigenstates)

- Compare to QED and QCD vertices: $P\,(\ \$\ \text{"}^{\mu}\ \$\ )\ =\ \$\ \text{"}^{\mu}\ \$$ (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.

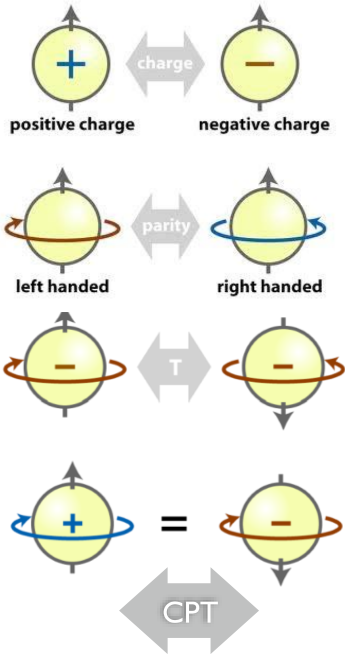
- ***CPT*** Theorem states:
  "All interactions described by a local Lorentz invariant gauge theory must be invariant under the combined operation ***CPT*** "

  !***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:

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

- 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.

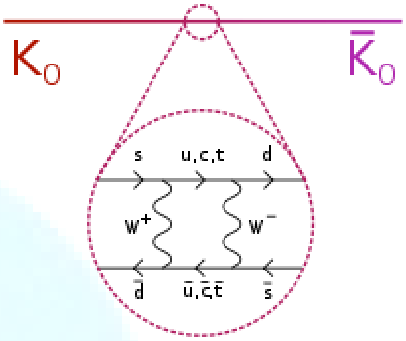
LHCb and the Matter-Antimatter Asymmetry

Neutral Meson Mixing

- Second order weak interactions can mix long-lived neutral mesons with their antiparticles:

"$\mathbf{K^0\,(\bar{s}\,d),\ D^0\,(\bar{c}\,u),\ B^0\,(\bar{b}\,d),\ B_s\,(\bar{b}\,s)}$ $\mathbf{K^0}$ ' $\mathbf{\bar{K}^0}$ $\mathbf{D^0}$ ' $\mathbf{\bar{D}^0}$ $\mathbf{B^0}$ ' $\mathbf{\bar{B}^0}$ $\mathbf{B_s}$ ' $\mathbf{\bar{B}_s}$

- e.g. take the neutral kaons $\mathbf{K^0}$ $\mathbf{\bar{K}^0}$ as an example:



- The

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

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

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 $\mathbf{\bar{K}^0}$
- Two common decay modes are **2&** and **3&**
  - **&^{0}&^{0}** and **&$^+$&$^!$** have ***CP*** **= +1**
  - **&^{0}&^{0}&^{0}** and **&$^+$&$^!$&^{0}** have ***CP*** **= !1**

Neutral Kaons continued

- ***CP*** is almost conserved in the decay of the neutral kaons.
- Decay **K(&&** has large phase space ⇒ quick decay, travels ~ cm before decay
- named “**K**-short” or $\mathbf{K_S}$ with $\mathbf{)_S}$ = **0.09 ns**
- Decay **K(&&&** has small phase space ⇒ slow decay, travels ~ 10 m before decay
- “**K**-long” or $\mathbf{K_L}$ with $\mathbf{)_L}$ = **51 ns**

- After a neutral kaon is produced, at some time, t, later it will be described by: $\psi(t) = a(t)|K^0 + b(t)|K^0$

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

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

$$\hat{M} - \frac{i}{2}\hat{\Gamma} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & \Delta m_K - \frac{i}{2}\Delta\Gamma_K \\ (\Delta m_K)^* \quad \frac{i}{2}(\Delta\Gamma_K)^* & M_K \quad \frac{i}{2}\Gamma_K \end{pmatrix} -$$

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- Mass difference $+m_K = m_S \, ! \, m_L = 3.52(1)$ x$10^{!12}$ MeV = 0.53 x $10^{!10}$ $s^{!1}$ is oscillation frequency

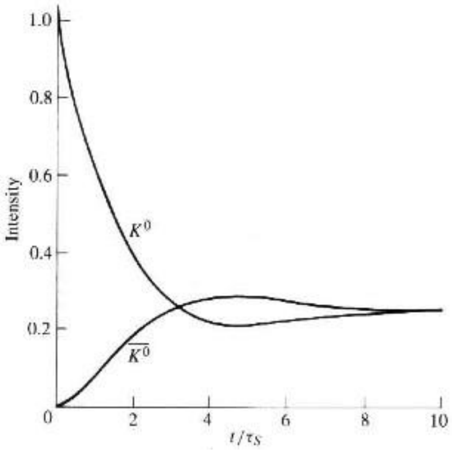
Time Evolution of K^0

$$K_S(t) = K_S(0)\exp\{-(\Gamma_S/2 + im_S)t\}$$

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

$$^0(t) = \frac{1}{4}\; e^{-\Gamma_L t} + e^{-\Gamma_S t} + 2\; e^{-\Gamma t}\cos\Delta m_K t$$

$$\overline{K}^0(t) = \frac{1}{4}\; e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2e^{-\Gamma t}\cos\Delta m_K t$$



- The time evolution of the **K_S** and **K_L** states are:

$$K_L(t) = K_L(0)\exp\{-(\Gamma_L/2 + im_L)t\}$$

K

- where * = **,** (*$_S$ + *$_L$)

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

Neutral Kaons with *CP* Violation

- The *CP* eigenstates are **K$_1$** and **K$_2$**

$$|K_1\rangle = \frac{}{\sqrt{2}} \quad |K^0\rangle - |\overline{K}^0\rangle \qquad CP = +1$$

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

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- The decay **K$_S$** and **K$_L$** are not quite the same as the decay eigenstates, instead in terms of a small parameter **!:**

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

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

- The decay states contain both ***CP*** = +**1** and ***CP*** = "**1**, ***CP*** is violated.

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$$|K_S = \_N\ (|K_1 - |K_2)$$

$$|K_L\rangle = \frac{1}{N}\left(|K_2\rangle + \epsilon|_{K_1}\right)$$

- **!** is measured to be |**!**| ~ **2 # 10**$^{"3}$, the amount of **indirect *CP* violation** due to mixing of different ***CP*** eigenstates **K$_1$** and **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 ! antimatter asymmetry of the universe.