2. Symmetries

2.5 CP (violation)
Charge Conjugation and Parity (CP)

We have seen that the weak interaction is not invariant under P and C transformation, but how about CP?

Example:
The Kaon System

Gell-Mann and Pais noted:

\[ CP|K^0\rangle = -|\bar{K}^0\rangle, \quad CP|\bar{K}^0\rangle = -|K^0\rangle \]

\[ |K_1\rangle = \left(\frac{1}{\sqrt{2}}\right)(|K^0\rangle - |\bar{K}^0\rangle) \quad \text{and} \quad |K_2\rangle = \left(\frac{1}{\sqrt{2}}\right)(|K^0\rangle + |\bar{K}^0\rangle) \]

\[ CP|K_1\rangle = |K_1\rangle \quad \text{and} \quad CP|K_2\rangle = -|K_2\rangle \]
The Kaon System

Assuming CP is conserved one concludes for $K_1$ and $K_2$ decays

$$K_1 \rightarrow 2\pi, \quad K_2 \rightarrow 3\pi$$

$$t_1 = 0.895 \times 10^{-10} \text{ sec}$$
$$t_2 = 5.11 \times 10^{-8} \text{ sec}$$

$$m_2 - m_1 = 3.48 \times 10^{-6} \text{ eV/c}^2$$

Perfect test of CP invariance!
Testing CP invariance

As $K_1$ decay much faster than $K_2$, a pure beam of $K_2$ can be produced from $K_0$ by letting all $K_1$ decay.

Finding $2\pi$ decays in the beam of $K_2$ is a clear indication of CP violation.

Croning and Fitch conducted this experiment in 1964. They counted 45 $2\pi$ events in 22700 decays.

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle)$$
Cronin and Fitch Experiment

EVIDENCE FOR THE \( 2\pi \) DECAY OF THE \( K^0_L \) MESON

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Testing CP invariance

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Semileptonic $K_L$ decays also show evidence for CP violation in

\[
\begin{align*}
(a) \quad \pi^+ + e^- + \bar{\nu}_e & \quad \text{or} \quad (b) \quad \pi^- + e^+ + \nu_e
\end{align*}
\]

More $K_L$ decay to positrons than into an electron by a fractional amount of $3.3 \times 10^{-3}$

CP violation has also been shown in B meson systems and tests in the neutrino sector are under way.
Matter - Antimatter Asymmetry

One of the biggest mysteries in physics!

1967, Sakharov proposed three necessary conditions that baryon generating interactions must satisfy to produce matter and antimatter at different rates

1) Baryon number violation
2) C and CP violation
3) Interaction out of equilibrium
<table>
<thead>
<tr>
<th></th>
<th>Bilinear</th>
<th>P</th>
<th>C</th>
<th>T</th>
<th>CP</th>
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<td>$\psi_2 \psi_1$</td>
<td>$\psi_1 \psi_2$</td>
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<tr>
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<tr>
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<tr>
<td>tensor</td>
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