Observation of CP Violation in Kaon Decays

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Outline

1. Theory
   i. Review of discrete symmetries
   ii. Violation of symmetries and the CPT Theorem
   iii. The Kaon System
      a. Mixing and eigenstates of CP
      b. Decay modes and regeneration

2. Experiment: Cronin, Fitch et. al.
   i. Setup
   ii. Analysis
   iii. Results
The discrete transformations discussed here have eigenvalues

$$\hat{O} |\psi\rangle = \lambda |\psi\rangle \quad \lambda = +1,-1$$

where the operator stands in for Charge Conjugation (C), Parity (P), and Time Reversal (T)

What are their eigenstates?
If $[\hat{O},\hat{H}] = 0$, that is if $\hat{O}$ has the same eigenstates as the Hamiltonian, then these energy eigenstates are said to have definite states of symmetry.
CPT Theorem

A local, Lorentz invariant quantum field theory with a Hermitian Hamiltonian must respect CPT symmetry.

- first appeared in the work of Julian Schwinger, then proven more explicitly by Lüders, Pauli and Bell.
- stands on solid ground theoretically and experimentally

Implications: individual violations of permutations of C, P and T must cancel. Thus, violation of CP would require violation of T, which would mean that

- time has a preferred direction on the fundamental scale.
- there is a clue to the matter-antimatter imbalance (the two are otherwise CP-symmetric)
Neutral Kaon Particles: \( K^0 = d\bar{s}; \quad \bar{K}^0 = \bar{d}s \)
- Neutral particle with a distinct (opposite strangeness) antiparticle
- Common decay products (e.g. 2\(\pi\))

**Consequence:** A neutral Kaon can oscillate into its antiparticle!

**Example:**

These must not be eigenstates of the full Hamiltonian!
Mixing Formalism:
Evidently, the strong interaction Hamiltonian*:

\[
H_{\text{strong}} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}
\]

eigenstates: \( K^0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) \( \overline{K}^0 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \)

acquires off-diagonal “mixing terms” due to the weak interaction:

\[
H = \begin{pmatrix} M & V \\ V & M \end{pmatrix}
\]

eigenstates: \( K_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \) \( K_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \)

eigenvalues: \( E_1 = M + V \) \( E_2 = M - V \)

Time evolution introduces oscillation:

\[
K_1 e^{-\frac{i}{\hbar}(M+V)t} + K_2 e^{-\frac{i}{\hbar}(M-V)t} = \sqrt{2} e^{-\frac{i}{\hbar}Mt} \begin{pmatrix} \cos \frac{V}{\hbar}t \\ i \sin \frac{V}{\hbar}t \end{pmatrix}
\]

\( K_1 \) and \( K_2 \) (imaginary) decay rates are added on the diagonal

* Rest frame assumed to avoid extra contributions to the energy.
Neutral Kaons as states of CP Transformation

*Problem:* Kaons are not good states of CP: \( CP(K^0) = -\bar{K}^0 \)

…but the eigenstates of the new Hamiltonian are:

\[
K_1 = \frac{1}{\sqrt{2}} \left( K^0 - \bar{K}^0 \right) \quad \Rightarrow \quad CP(K_1) = \frac{1}{\sqrt{2}} \left( -\bar{K}^0 + K^0 \right) = K_1 \quad \langle CP \rangle = +1
\]

\[
K_2 = \frac{1}{\sqrt{2}} \left( K^0 + \bar{K}^0 \right) \quad \Rightarrow \quad CP(K_2) = \frac{1}{\sqrt{2}} \left( \bar{K}^0 + K^0 \right) = -K_2 \quad \langle CP \rangle = -1
\]

Success? CP and the Hamiltonian have simultaneous eigenstates – CP must be conserved, i.e. symmetry states maintained:

\[
K_1 \rightarrow 2\pi \quad \langle CP \rangle_{2\pi} = +1
\]

\[
K_2 \rightarrow 3\pi \quad \langle CP \rangle_{3\pi} = -1
\]

Is this true or can we find: \( K_2 \rightarrow 2\pi \quad \langle CP \rangle : -1 \rightarrow +1 \)
### The Kaon System

#### Experimental Perspective

<table>
<thead>
<tr>
<th>$\tau$ (s)</th>
<th>Main decay modes</th>
<th>$\Gamma_i / \Gamma$</th>
<th>Experimental use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>$\pi^+\pi^-$</td>
<td>69.2%</td>
<td>← useful for calibration, conveniently short lifetime</td>
</tr>
<tr>
<td></td>
<td>$\pi^0\pi^0$</td>
<td>30.7%</td>
<td></td>
</tr>
<tr>
<td>$K_2$</td>
<td>$\pi^+l^-\nu_l$ or conj. ($K_{13}$)</td>
<td>67.6%</td>
<td>interesting potential source of CP violation; can regenerate $K_1$</td>
</tr>
<tr>
<td></td>
<td>$3\pi^0$</td>
<td>19.6%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pi^+\pi^-\pi^0$</td>
<td>12.6%</td>
<td></td>
</tr>
</tbody>
</table>

#### Regeneration

$$K_2 = \frac{1}{\sqrt{2}} \left( K^0 + \overline{K}^0 \right) \quad \Rightarrow \quad \overline{K}^0 + p \rightarrow \Lambda^0 + \pi^+$$

strong interactions: must conserve strangeness

leave little free energy – unlikely!

$K^0$ remains, so $K_1$ is back! (in superposition with $K_2$)
Insertable tungsten target for regeneration

$K_1$ decayed away by this point to avoid interactions, regeneration etc.

Experiment by Cronin, Fitch et. al.
$2\pi$ decay filtering method:

- both particles are captured: invariant mass of $K^0$ expected
- forward direction ($\theta = 0$) for the vector sum of the two momenta

Not so for other possible (3-body) decays – $K_{e3}$, $K_{\mu3}$, $K_{\pi3}$: decay products are lost. Result:

- invariant mass is undercounted
- $\theta \neq 0$

Approach to calibration and measurement

Regenerate $K_1$ and measure $\theta$ and $m$ distributions of $2\pi$ decay and compare with those of $K_2$ if such decays are found.
The result of “mass undercounting”: mass spectrum spreads and shifts below the $K^0$ mass.

Cutting on $K^0$ mass and looking for a forward peak in the $\cos \theta$ distribution (sign of 2-body decay)…

2$\pi$ decay invariant mass and angle distributions are the same as those from regenerated $K_1$

<table>
<thead>
<tr>
<th></th>
<th>inv. mass (MeV)</th>
<th>peak angle (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>498.1±0.4</td>
<td>3.4±0.3</td>
</tr>
<tr>
<td>$K_2$</td>
<td>499.1±0.8</td>
<td>4.0±0.7</td>
</tr>
</tbody>
</table>
Results

So, having subtracted the background as shown and taken into account relative detection efficiencies, there were found $45 \pm 9$ CP-violating $\pi^+\pi^-$ decays out of a total of 22700 events. This corresponds to a branching ratio of $0.20 \pm 0.04\%$.

Reported:

**Volume 13, Number 4**

**PHYSICAL REVIEW LETTERS**

27 July 1964

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


Princeton University, Princeton, New Jersey

(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the $2\pi$ decay of the $K^0$ meson. Several previous experiments have

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, $m^*$, assuming
Evidently, the short and long-lived particles (i.e. energy eigenstates having distinct decay rates) previously thought to be eigenstates of CP are in fact:

\[ K_S^0 \approx K_1^0 + \varepsilon K_2^0 \]

\[ K_L^0 \approx K_2^0 + \varepsilon K_1^0 \]

where \( K_1 \) and \( K_2 \) are the pure eigenstates of CP and \( \varepsilon \) is the degree of violation. Calculated in the analysis of the original experiment:

\[ |\varepsilon| = 2.3 \times 10^{-3} \]
The presented results lead to the following conclusions:

- the Weak interaction slightly violates CP symmetry
- by the CPT theorem, it violates T symmetry as well – a preferred direction on the elementary particle scale!
- a small (and not yet satisfactory) degree of CP violation has been verified in the theory of matter-antimatter imbalance.