CP Violation &
Matter anti-Matter Asymmetry

Lecture II

SLAC Summer Institute 2022

Hassan Jawahery
University of Maryland
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Outline of Lecture II

- The puzzle of matter-antimatter asymmetry

- Discovery of CP violation in the Neutral Kaon system: A brief historical overview

- Preparing for CP Violation studies beyond kaons: Discovery of the other Meson ↔ Antimeson oscillations: $B_d^0 \leftrightarrow \bar{B}_d^0$, $B_s^0 \leftrightarrow \bar{B}_s^0$, $(D^0 \leftrightarrow \bar{D}^0)$
Outline of Lecture IV

- CP Violation beyond kaons:
  - Verification of the CPV mechanism in the Standard Model

- Search for CPV beyond SM

- Outlook for Flavor and CPV Experiments in the next two decades

- Summary
Acknowledgments/References

Some suggested readings as well as sources of experimental plots

- J. Cronin and V. Fitch Nobel lectures

- Discreet Symmetries and CP Violation (M.S. Sozzi)
- Physics of the B factories (BaBar & Belle) (1406.6311)
- Physics case for LHCb upgrade-II (CERN-LHCC-2018-027)

- Heavy Flavor Averaging group (HFLAV) (https://hflav.web.cern.ch)
- CKMfitter (http://ckmfitter.in2p3.fr)
- Utfit (http://www.utfit.org/UTfit/)
Antimatter vs Matter

The realization of relativistic quantum mechanics - The Dirac Equation - revealed the existence of antiparticles in nature.

For every known elementary particle, there is an antiparticle counterpart of the same mass and lifetime (CPT Theorem) but with the additive quantum numbers reversed. Some are their own antiparticle.
Antimatter vs Matter: CPT tests

Has passed all CPT test- so far

\[ m(a) = m(\bar{a}) \]
\[ \tau(a) = \tau(\bar{a}) \]

equal and opposite EM properties; identical energy levels in atoms and their antimatter counterparts,…

From CERN Antimatter Decelerator (AD)

- Antihydrogen spectrum
Laser driven 1s-2s transition

\[ \Delta f = 2 \times 10^{-12} \]

\[ \begin{array}{|c|c|}
\hline
\text{Quantity} & \text{Value} \\
\hline
m(e^+) - m(e^-) & < 8 \cdot 10^{-9} m_e \\
Q(e^+) + Q(e^-) & < 4 \cdot 10^{-8} e \\
g(e^+) - g(e^-) & (-0.5 \pm 2.1) \cdot 10^{-12} g_e \\
m(p) - m(p) & < 1 \cdot 10^{-8} m_p \\
|Q(\bar{p})/m(\bar{p})| - Q(p)/m(p) & (-9 \pm 9) \cdot 10^{-11} |e|/m_p \\
\tau(\mu^+) - \tau(\mu^-) & (2 \pm 8) \cdot 10^{-5} \tau_\mu \\
\tau(\pi^+) - \tau(\pi^-) & (5.5 \pm 7.1) \cdot 10^{-4} \tau_\pi \\
\tau(K^+) - \tau(K^-) & (0.11 \pm 0.09)\% \tau_K \\
|m(K^0) - m(\bar{K}^0)| & < 10^{-18} m_K \\
\hline
\end{array} \]

From M.S. Sozzi (Discrete Symmetries)
[Compiled from Particle data group (PDG)]
Antimatter vs Matter
Is the universe matter-antimatter symmetric?

Paul A. M. Dirac

Theory of electrons and positrons
Nobel Lecture, December 12, 1933

The theory of electrons and positrons which I have just outlined is a self-consistent theory which fits the experimental facts so far as is yet known. One would like to have an equally satisfactory theory for protons. One might perhaps think that the same theory could be applied to protons. This would require the possibility of existence of negatively charged protons forming a mirror-image of the usual positively charged ones.

In any case I think it is probable that negative protons can exist, since as far as the theory is yet definite, there is a complete and perfect symmetry between positive and negative electric charge, and if this symmetry is really fundamental in nature, it must be possible to reverse the charge on any kind of particle. The negative protons would of course be much harder to produce experimentally, since a much larger energy would be required, corresponding to the larger mass.

If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods.
Anti-Matter puzzle:
No trace of primary antimatter in the cosmos

- Measured energy spectrum of cosmic ray $\gamma$'s shows no evidence for the expected features from matter-antimatter annihilations
- No evidence for primary antiprotons in cosmic rays

Excellent reviews: P. Coppi (SSI 2004), G. Steigman (1976)

- Measurements of antiproton component of cosmic rays $\bar{p}/p \approx 10^{-4}$ consistent with secondary production from interactions of (matter) cosmic rays:
  Observation of heavier anti-nuclei (e.g. antihelium) would constitute a very strong, low background signature of primary antimatter: extremely low rate expected in cosmic rate interactions. AMS has reported a few antihelium candidates (CERN Colloquium)- vs 3.7 billion helium candidates- still unpublished- Wait for their final word.
In the Standard Model of Cosmology, the universe starts with: 
\[ N(\text{Baryons}) = N(\text{anti-Baryons}) \]

Today: matter dominated universe with 
\[ \frac{n(\text{Baryons})}{n_\gamma} \sim 6 \times 10^{-10} \]

What happened to the antimatter? (Why is there any matter left? )

In 1967, Sakharov proposed the conditions under which a Matter-Antimatter symmetric early universe could evolve into a matter dominated universe:

1. Baryon non-conservation
2. C and CP violation (properties of matter and antimatter are different)
3. Non thermal equilibrium condition

The proposal came after the 1964 discovery of CP violation in kaons. But the observed CPV, consistent with SM, is considered insufficient to account for the observed baryon imbalance in the universe.

(Jure Zupan may comment further on baryogenesis in his 2nd lecture)
Anti-Matter puzzle: (3)
Antimatter vs Matter in interactions

The only evidence, thus far, for differences in the interaction properties of matter vs antimatter is the observation of CP violation in Weak Interactions (in the quark sector):

- First observed in neutral kaons (1964)
- In the B (bottom) system (2001)
- In the Charm system (2019)

Enormous effort underway to measure CPV in the lepton sector (covered elsewhere).
The first assault on the sacred discreet symmetries: P, C, T

- **τ − θ puzzle** (1950's): two long-lived particles, with similar masses, lifetimes, abundance & interactions properties, but different apparent parity:

  \[ K^+(\varphi^+ \rightarrow \pi^+\pi^0, P = +1), \quad K^+(\tau \rightarrow \pi^+\pi^+\pi^-, P = -1) \]

  inspired Lee and Yang (1956) to examine evidence for conservation of parity in weak interactions and propose experimental tests.

  \[ \Rightarrow \] P & C shown to be maximally broken in Weak Interactions (Wu 1957)

(covered in other lectures)
The Kaon system: (a brief history)

One of the most powerful instruments of discovery in particle physics

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For a while CP symmetry seemed to be intact; Landau proposed CP as the appropriate “mirror” symmetry in nature
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- The other shoe dropped in 1964: Christenson, Cronin, Fitch and Turlay showed that CP is Broken in Neutral Kaon Decays

  \( \Rightarrow \) Led to the CKM mechanism to accommodated CPV in the SM, requiring the 3rd fermion generation (Kobayashi, Maskawa 1973)
The Kaon system: (a brief history)
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- Suppressed \( K_L \rightarrow \mu^+\mu^- \): Glashow-Illiopoulos-Mianni (GIM) Mechanism (1970)
  \( \Rightarrow \) Predicted the fourth quark (charm),
    \( K^0 \leftrightarrow \bar{K}^0 \) mixing: (Gaillard, Lee 1974) approximate range of charm mass
The Neutral Kaon System

$K^0 \leftrightarrow \bar{K}^0$ Oscillation

Gell-Mann - Pais Theory

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,∗ Department of Physics, Columbia University, New York, New York

AND

A. Pais, Institute for Advanced Study, Princeton, New Jersey

(Received November 1, 1954)

Some properties are discussed of the $\theta^0$, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and $K$ particles, the $\theta^0$ possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, the $\theta^0$ must be considered as a “particle mixture” exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all $\theta^0$'s undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.
Neutral Kaon Oscillations
Gell-Mann - Pais Theory

Flavor (Strong) eigenstates

<table>
<thead>
<tr>
<th>K^0 (\bar{s}d)</th>
<th>(S=+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\Kbar^0 (sd)</td>
<td>(S=-1)</td>
</tr>
</tbody>
</table>

K^0 \leftrightarrow \Kbar^0 Possible in Weak interactions
[Strangeness is not conserved in WI]

Time evolution of the coupled 2-state quantum system \( \begin{pmatrix} K^0 \\ \Kbar^0 \end{pmatrix} \) governed by:

\[
\frac{id}{dt} \begin{pmatrix} K^0 \\ \Kbar^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\ M_{21} - \frac{i}{2} \Gamma_{21} & M_{22} - \frac{i}{2} \Gamma_{22} \end{pmatrix} \begin{pmatrix} K^0 \\ \Kbar^0 \end{pmatrix}
\]

Predicts two different neutral kaons (eigenstates) -assuming CP symmetry

\[
|K_1> = \frac{1}{\sqrt{2}} (|K^0> - |\Kbar^0>)
\]

CP |K_1> = +|K_1>

\[
|K_2> = \frac{1}{\sqrt{2}} (|K^0> + |\Kbar^0>)
\]

CP |K_2> = - |K_2>
Neutral Kaon Oscillations

Gell-Mann – Pais Theory

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

\( CP \ |K_1 \rangle = + |K_1 \rangle \)

\( K_1 \rightarrow \pi\pi \) (short lived) \((K_s)\)

\( \tau_s = 0.9 \cdot 10^{-10} s \)

|\( K_2 \rangle = \frac{1}{\sqrt{2}} (|K^0 \rangle + |\bar{K}^0 \rangle) |

\( CP \ |K_2 \rangle = - |K_2 \rangle \)

\( K_2 \rightarrow \pi\pi\pi \) (Long lived) \((K_L)\)

(phase space suppressed)

\( \tau_L = 0.5 \cdot 10^{-7} s \)

A small mass difference: \( \Delta m \propto <K^0 |H_w|\bar{K}^0 > \)

\( =(3.842 \pm 0.011) \times 10^{-6} \text{ eV}/c^2 \)

Some of the key consequences of \( K^0 \leftrightarrow \bar{K}^0 \) oscillation:

- Non- exponential time evolution of a state starting as \( K^0 \) (or \( \bar{K}^0 \))
  (mix of \( K_s \) & \( K_L \))

- Kaon Regeneration
**A consequence of** $K^0 \leftrightarrow \bar{K}^0$ **Oscillation**

**Non-exponential time evolution of the** $K^0$ **system**

**Time evolution of a** $K^0$ **meson produced in strong interactions:**

At $t=0$

$$|K_0(0)\rangle = \frac{1}{\sqrt{2}} (|K_1\rangle + |K_2\rangle)$$

$$|K_0(t)\rangle = \frac{1}{\sqrt{2}} (e^{-\frac{t}{2\tau_S}} i m_1 t |K_1\rangle + e^{-\frac{t}{2\tau_L}} i m_2 t |K_2\rangle)$$

**The probability to be in states** $K^0$ **or** $\bar{K}^0 **after time**$ t$

$$P[K^0(t=0) \rightarrow K^0(t) (\bar{K}^0(t))] = \frac{1}{4} \left[ e^{-\frac{t}{\tau_S}} + e^{-\frac{t}{\tau_L}} \pm 2 \cos(\Delta m t) e^{-\frac{t}{2(\tau_S + \tau_L)}} \right]$$

**Diagram**

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

A pure $K_L$ beam
**Another consequence of \( K^0 \leftrightarrow \bar{K}^0 \) Oscillation**

**Kaon Regeneration**

\[ K^0 (S = +1) \text{ and } \bar{K}_0 (S = -1) \text{ interact differently with matter:} \]

\[ \bar{K}_0 (s\bar{d}) \text{ are more likely to be absorbed.} \]

Thus, starting with a \( K_L \) beam into a slab of material, the mix of \( K^0 \) and \( \bar{K}_0 \) changes when the beam emerges from the slab.

\[ \Rightarrow \text{Both } K_S \text{ and } K_L \text{ beams will appear behind the plate (regeneration)} \]

\[ |K_L \rangle = \frac{1}{\sqrt{2}} (|K^0 \rangle + |\bar{K}^0 \rangle) \]

Regenerated \( K_S \) beam develops a forward going coherent component, with nearly same phase and momentum as initial \( K_L \) beam.

\[ \psi \sim |K_L \rangle + |A_r| e^{i\phi_r} |K_S \rangle \]

*Fig. from Stefan Paul*
Another consequence of $K^0 \leftrightarrow \bar{K}^0$ Oscillation

**Kaon Regeneration**

$K^0(S = +1)$ and $\bar{K}_0(S = -1)$ interact differently with matter: $\bar{K}_0(s \bar{d})$ are more likely to be absorbed.

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Regenerated $K_S$ beam develops a forward going coherent component, with nearly same phase and momentum as initial $K_L$ beam

\[
\psi \sim |K_L> + |A_r|e^{i\Phi_r}|K_S>
\]

$A_r \propto \left(f(0) - \bar{f}(0)\right)$ - forward scattering amplitudes for $K^0$ & $\bar{K}^0$ - estimated with the aid of optical theorem and cross-sections for $K^-p$ and $K^+p$
A puzzling result

They found excess of regenerated $K_1^0 \rightarrow \pi^+\pi^-$

Attribute it to possible “new weak long-range interaction between proton and kaon”

But also “Can not exclude the possibility that the striking character of the data results from a combination of real effects underestimated by us together with strong statistical fluctuations.”
The CP Violation experiment
(Christenson, Cronin, Fitch, Turlay)

- The experiment was aimed at studying regeneration effects and exploring the anomalous result of Leipuner et al.

- Performed at the AGS synchrotron (Brookhaven National Lab)

- Spark chambers played a decisive role in the success of the experiment

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of $K^0$ mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K_2^0 + \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2^0 \rightarrow \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of $K_1^0$'s in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortunately the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming $\mu^-p$ scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the $m^*$ or the $Q$ value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.
The CP Violation experiment

A pure $K_L$ beam is obtained from an initial $K^0$ beam travelling 57 feet from the production point.

[ Initial $K^0$ beam produced in proton beam (30 GeV) on a Beryllium Target ]

- The spectrometer calibrated for $K_{S(L)} \to \pi\pi$ decays by inserting slabs of material before the $K_L$ beam in different locations.
- The number of regenerated $K_S \to \pi\pi$ events in He gas estimated to be negligible.
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![Diagram of the CP Violation experiment setup]
The momentum of true two-body $K_L \rightarrow \pi\pi$ decays must lineup with the direction of $K_L$ beam.

Flat distribution for backgrounds from 3-body decays - below and above the Kaon mass region.

- 45±9 events in the kaon mass region and forward peak ($cos \theta > 0.9999$)-after background subtraction.

- With negligible contribution expected from coherent regeneration of $K_S$ in He, all 45 events attributed to the CP Violating $K_L \rightarrow \pi^+ \pi^-$ decay.

$$BR = \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \text{all charged modes})} = (2.0 \pm 0.4) \cdot 10^{-3}$$

Distribution of $cos \theta$ - the angle between the $\pi\pi$ system and the $K_L$ beam direction.
Not easily accepted, initially. But subsequent experiments showing interference of regenerated $K_s \to \pi^+\pi^-$ beam and $K_L \to \pi^+\pi^-$ decays, provided conclusive proof that the observed events were indeed from the $CP$ violating $K_L \to \pi^+\pi^-$ ruled out the presence of an accompanying very low energy light particle and other interpretations of the results.
EVIDENCE FOR CONSTRUCTIVE INTERFERENCE BETWEEN COHERENTLY REGENERATED AND CP-NONCONSERVING AMPLITUDES*

V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 3 June 1965)

Diffuse beryllium regenerator

CPV amplitude

\[ \eta_{+-} = \frac{A(K_S \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} \]

Regeneration amplitude

\[ A_r = i \pi N_r \Lambda \left( \frac{f - \bar{f}}{k} \right) / (i \Delta m + \frac{1}{2}) \]

\[ \psi(\pi^+ \pi^-) \sim \eta_{+-} |K_L > + |A_r| e^{i \phi_r} |K_S > \]

For \(|A_r| \sim |\eta_{+-}|\), \((\pi^+ \pi^-)\) rate was found to be \(~4\times\) (the rate for \(|A_r| \sim 0\)) vs a factor of two, for incoherent sum- Evidence for constructive interference
Several classic interference experiments: Interference of \((\pi^+\pi^-)\) from regenerated \(K_s \rightarrow \pi^+\pi^-\) with \((\pi^+\pi^-)\) from \(K_L \rightarrow \pi^+\pi^-\) led to measurements of \((\phi_{\pi\pi} - \phi_{A^r})\) & \(\Delta m\).

**Observation of interference conclusively demonstrated that the observed the \(K_L\) decay candidates are the CP violating \(K_L \rightarrow \pi^+\pi^-\) decays.**

Fig. 13. Measured event rate as a function of regeneration amplitude. The solid curves are the results of best \(\chi^2\) fits to the data for interference angles of 0, \(\pi/2\), and \(\pi\). Only the curve for 0 angle gives a good fit to the data.
Possible origin of the observed CP violation (1)

(1) The physical states $K_L$ and $K_s$ are not pure CP eigenstates: They contain a small amount of the opposite CP state ($\epsilon$)

$$\left|K_s\right> = \frac{1}{\sqrt{2(1+\epsilon^2)}} \left[ (1 + \epsilon)\left|K^0\right> - (1 - \epsilon)\left|\bar{K}^0\right> \right]$$

$$\left|K_L\right> = \frac{1}{\sqrt{2(1+\epsilon^2)}} \left[ (1 + \epsilon)\left|K^0\right> + (1 - \epsilon)\left|\bar{K}^0\right> \right]$$

$$\left|K_L\right> = \frac{1}{\sqrt{1+\epsilon^2}} \left[ \left|K_2\right> + \epsilon\left|K_1\right> \right]$$

Lincoln Wolfenstein (1964) proposed:
A CP violating superweak ($\Delta S=2$) interaction (with coupling $\sim 10^{-7} G_F$) responsible for $K^0 \leftrightarrow \bar{K}^0$ oscillations & the observed CPV

$\Rightarrow$ CPV in all modes is essentially governed by $\epsilon$
Possible origin of the observed CP violation (1)

(2) CP violation in weak interactions—Within SM via the CKM mechanism. Thus, CPV in decay (direct CP violation):

Consequence of \(|A(K^0 \rightarrow \pi\pi)| \neq |A(\bar{K}^0 \rightarrow \pi\pi)|\) (due to the presence of two contributing amplitudes)

\[ |K_L| = \frac{1}{\sqrt{1+\epsilon^2}} \left[ |K_2| + \epsilon |K_1| \right] \]

Direct CPV

Quantified by

\[ \epsilon' \]

\[ \epsilon \]

CPV via mixing

\[ (\pi\pi) \]

Must look for CPV in other modes

30#
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*direct CPV*
Quantified by

$\epsilon' \quad \epsilon$  
CPV via mixing
($\pi\pi$)

Must look for CPV in other modes

The $\pi\pi$ system can be in
$I=0$
$A_0 = \langle \pi\pi(I=0) | H_W | K_L \rangle$

$I=2$
$A_2 = \langle \pi\pi(I=2) | H_W | K_L \rangle$

different Clebsh-Gordon Coeffs for projecting $(\pi\pi) \to \pi^+\pi^- \; & \; (\pi\pi) \to \pi^0\pi^0$

$\Rightarrow$ different CPV asymmetries
for $K_L \to \pi^+\pi^- \; & \; K_L \to \pi^0\pi^0$
Possible origin of the observed CP violation (1)

(2) CP violation in weak interactions—Within SM via the CKM mechanism. This CPV in decay (direct CP violation);

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$$|K_L > = \frac{1}{\sqrt{1+\epsilon^2}} [ |K_2 > + \epsilon |K_1 > ]$$

direct CPV

Quantified by

$\epsilon'$

CPV via mixing

$\epsilon$

Must look for CPV in other modes

The $\pi\pi$ system can be in

$I=0$

$A_0 = < \pi\pi (I = 0) | H_w | K_L >$

$I=2$

$A_2 = < \pi\pi (I = 2) | H_w | K_L >$

different Clebsh-Gordon Coeffs for projecting $(\pi\pi) \to \pi^+\pi^- \& (\pi\pi) \to \pi^0\pi^0$

$\Rightarrow$ different CPV asymmetries for $K_L \to \pi^+\pi^- \& K_L \to \pi^0\pi^0$

$$\eta_{00} = \frac{<\pi^0\pi^0|H_w|K_L>}{<\pi^0\pi^0|H_w|\bar{K}_S>} = |\eta_{00}| e^{i\phi_{00}} = \epsilon - 2\epsilon'$$

$$\eta_{+-} = \frac{<\pi^+\pi^-|H_w|K_L>}{<\pi^+\pi^-|H_w|\bar{K}_S>} = |\eta_{+-}| e^{i\phi_{+-}} = \epsilon + \epsilon'$$

The $\pi\pi$ system can be in $I=0$ $A_0 = < \pi\pi (I = 0) | H_w | K_L >$ $I=2$ $A_2 = < \pi\pi (I = 2) | H_w | K_L >$

different Clebsh-Gordon Coeffs for projecting $(\pi\pi) \to \pi^+\pi^- \& (\pi\pi) \to \pi^0\pi^0$

$\Rightarrow$ different CPV asymmetries for $K_L \to \pi^+\pi^- \& K_L \to \pi^0\pi^0$
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Consequence of $|A(K^0 \to \pi\pi)| \neq |A(\bar{K}^0 \to \pi\pi)|$ (due to the presence of two contributing amplitudes)

$|K_L> = \frac{1}{\sqrt{1+\epsilon^2}} [|K_2> + \epsilon |K_1>]$

direct CPV
Quantified by

$\epsilon'$

$\epsilon$

CPV via mixing

For Superweak: No direct CPV ($\epsilon'$=0)

$\eta_{+-} = \eta_{00}$

The $\pi\pi$ system can be in $I=0$

$A_0 = <\pi\pi(I=0)|H_w|K_L>$

$I=2$

$A_2 = <\pi\pi(I=2)|H_w|K_L>$

different Clebsh-Gordon Coeffs for projecting $(\pi\pi) \to \pi^+\pi^- \& (\pi\pi) \to \pi^0\pi^0$ => different CPV asymmetries for $K_L \to \pi^+\pi^- \& K_L \to \pi^0\pi^0$

$\eta_{00} = \frac{<\pi^0\pi^0|H_w|K_L>}{<\pi^0\pi^0|H_w|K_s>} = |\eta_{00}|e^{i\phi_{00}}=\epsilon - 2\epsilon'$

$\eta_{+-} = \frac{<\pi^+\pi^-|H_w|K_L>}{<\pi^+\pi^-|H_w|K_s>} = |\eta_{+-}|e^{i\phi_{+-}}=\epsilon + \epsilon'$
Major Experimental programs carried out over three decades to measure direct CPV ($\epsilon'$) in kaon decays

Calculation of $\epsilon'$ is extremely difficult- still on-going

Experimental measurement also very difficult- took a long to show $\epsilon'$ is non-zero
Major Experimental programs carried out over three decades to measure direct CPV (\(\epsilon'\)) in kaon decays

Calculation of \(\epsilon'\) is extremely difficult- still on-going

Experimental measurement also very difficult- took a long to show \(\epsilon'\) is non-zero

Time evolution
From/Sozzi-Mannelli

By 2002: \(\epsilon'\) is non-zero

\[
\text{Re} \left( \frac{\epsilon'}{\epsilon} \right) = (16.6 \pm 2.3) \times 10^{-4}
\]

Superweak is ruled out as the sole source of CPV in kaons
Major Experimental efforts carried out over three decades to measure direct CPV ($\epsilon'$) in kaon decays

Calculation of $\epsilon'$ is extremely difficult - still on-going

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By 2002: $\epsilon'$ is non-zero

$$\text{Re} \left( \frac{\epsilon'}{\epsilon} \right) = (16.6 \pm 2.3) \times 10^{-4}$$

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Difficult to compute theoretically

Not sufficient for verification of the CKM
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2001: B factories also established CPV in B decays
Broader Program of CPV studies in kaons

What is discusses here is only a very small part of decades of studies of CPV in kaons. My apologies for not being able to cover the many beautiful measurements performed since observation of CPV in kaons.

A partial list includes:
- Measurements of the charge asymmetry: $K_L \to \pi^+ l \nu$ vs $K_L \to \pi^- l \nu$
- Series of interference experiments measuring the magnitude and sign of $\Delta m$ and the relative phase of CPV and regeneration amplitudes.
- CPV studies in charged kaons and hyperons leading to limits on CPV effects.
- Studies of CPV in $K_s$ decays in e+e- colliders (VEPP and DAΦNE) leading to limits.
- Studies of T-violation in kaons (CPLEAR)
1980: V. Fitch and J. Cronin awarded Physics Nobel Prize for their discovery of CP violation in kaons

At the time, the neutral Kaon system was the only known source of observed CPV. Origin still unclear (non-zero $\epsilon'$ not yet settled). The CKM picture yet to be tested.

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Whether the $CP$ violation that we observe today is a "fossil remain" of these conjectured events in the early universe is a question that cannot be answered at present. This is to say, does the $CP$ violation we observe today provide supporting evidence for these speculations? We simply do not know enough about $CP$ violation. Our experimental knowledge is limited to its observation in only one extraordinarily sensitive system that nature has provided us. We need to know the theoretical basis for $CP$ violation, and we need to know how to reliably extrapolate the behavior of $CP$ violation to the very high energies involved.

There are, however, on the horizon new systems which show some promise of giving additional information about $CP$ violation. These are the new neutral mesons, $D^0, B^0, B_s$ (composed of $c\bar{u}$, $b\bar{d}$, and $b\bar{s}$ quarks), and their antiparticles $\bar{D}^0, \bar{B}^0, \bar{B}_s^0$. These mesons have the same general properties as $K$ mesons. They are neutral particles that, with respect to strong interactions, are distinct from their own antiparticles, and yet are coupled to them by common weak decay modes. While we may not expect any stronger $CP$ impurities on the eigenstates (the parameter analogous to $\epsilon$), we might expect stronger effects in the decay amplitudes (the parameter analogous to $\epsilon'$). We might expect this since the $CP$ violation comes about through the weak interactions of the heavy quarks, $c, b, t$, which participate only virtually in $K$ decay, but can be more influential in heavy neutral meson decay. At present, $D$ mesons can be made rather copiously at the $e^+e^-$ storage ring SPEAR at SLAC, (Lüth, 1979) and $B$ mesons are beginning to be produced at the $e^+e^-$ storage ring CESR at Cornell (Andrews et al., 1980; Finocchiaro et al., 1980).
1980: V. Fitch and J. Cronin awarded Physics Nobel Prize for their discovery of CP violation in kaons

Kaon system was the only known source of observed CPV
Origin still unclear
The CKM picture yet to be tested
The required elements of a program for CPV Measurements in the B system

Measure indirect CPV due to interference of the decay and mixing amplitudes in modes common to \( B^0 \) and \( \bar{B}^0 \) (e.g. \( B \to J/\psi K_S \))
The required elements of a program for CPV Measurements in the B system

NOTES ON THE OBSERVABILITY OF CP VIOLATIONS IN B DECAYS

I.I. BIGI
Institut für Theor. Physik der RWTH Aachen, D-5100 Aachen, FR Germany

A.I. SANDA¹
Rockefeller University, New York 10021, USA

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We describe a general method of exposing CP violations in on-shell transitions of B mesons. Such CP asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large CP asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing CP tests with a high statistics B meson factory like the $Z^0$ (and a toponium) resonance.

And Carter & Sanda (1980)

Measure indirect CPV due to interference of the decay and mixing amplitudes in modes common to $B^0$ and $\bar{B}^0$ (e.g. $B \rightarrow J/\psi K_S$)

\[ \phi_d \]
\[ f_{cp} \]
\[ \phi_m \]
\[ B^0 \]
\[ \bar{B}^0 \]
\[ f_{cp} \]

Requires $B^0 \leftrightarrow \bar{B}^0$ oscillation for this scheme to work

Appropriate decay channels for CPV measurements are rare, thus, the need for large number of B’s (B Factory)
Observation of $B^0 \leftrightarrow \bar{B}^0$ Oscillation

UA1 at SPS (1987): First report of Excess of like-sign dileptons

Excess of same sign di-leptons, ARGUS (1987)

Evidence for

$$\gamma(4S) \rightarrow B^0 \bar{B}^0 \rightarrow \ell^+\ell^-$$

$$r = \frac{\Gamma(B^0 \rightarrow \bar{B}^0 \rightarrow X^{'})}{\Gamma(B^0 \rightarrow X)} = 0.21 \pm 0.08$$

Confirmation from CLEO 1988

$$r = 0.19 \pm 0.08$$
$B^0 \leftrightarrow B^0$ oscillation in the SM

$$\Delta M = \frac{G_F^2 m_b B_B f_B^2 | V_{bt}^* V_{td} |^2 m_t^2 A \left( \frac{m_t^2}{m_W^2} \right) \eta_{QCD}}{6\pi^2}.$$  

$$r \approx \frac{1}{2} \left( \frac{\Delta M}{\Gamma} \right)^2 = 0.21 \pm 0.08$$

$\Rightarrow M(\text{top}) > 50 \text{ GeV}$

At the time the top quark was expected to be much lighter
$B^0 \leftrightarrow \bar{B}^0$ oscillation  

Time evolution of a state prepared as $B^0$

$\Delta m_{d} = 0.5065 \pm 0.0019$ ps$^{-1}$  
$\propto m_t^2 |V_{tb}^* V_{td}|^2$  
Negligible $\Delta \Gamma_d$

$\Delta m_{s} = 17.741 \pm 0.020$ ps$^{-1}$  
(first measurements by CDF & D0)  
$\propto m_t^2 |V_{tb}^* V_{ts}|^2$  
$\Delta \Gamma_s / \Gamma_s \sim +0.124$
$D^0(c\bar{u}) \leftrightarrow \bar{D}^0(\bar{c}u)$ oscillation

D$^0$ Mixing is small, but now firmly established from:

(1) observation of mixing induced interference effects in the time-evolution of $D^0$ ($t=0$) decays in flavor eigenstates

&

(2) measurements of $D^0$ lifetime in CP eigenstates

BaBar, Belle, CDF, LHCb

\[ X = \frac{\Delta m}{\Gamma} \]

\[ y = \frac{\Delta \Gamma}{2\Gamma} \]
The 2-state quantum system of Meson-AntiMeson

Meson-AntiMeson Oscillations now established in all four Neutral Meson systems

\[
K \sim \bar{s}d, \quad D \sim \bar{c}u, \quad B_d \sim \bar{b}d, \quad B_s \sim \bar{b}s, \\
\bar{K} \sim sd, \quad \bar{D} \sim \bar{c}u, \quad \bar{B}_d \sim b\bar{d}, \quad \bar{B}_s \sim b\bar{s},
\]

The only hadrons that transform into their corresponding antiparticles. This happens through the suppressed Flavor-Changing-Neutral-Current process. Serves a powerful tool in CP violation studies in Neutral Mesons, in tests of quantum mechanics,

Feynman characterized the successful description of the neutral system of K mesons “one of the greatest achievements of theoretical physics."

**Feynman lectures volume III**

If there is any place where we have a chance to test the main principles of quantum mechanics in the purest way—does the superposition of amplitudes work or doesn’t it?—this is it. In spite of the fact that this effect has been pre-
Next lecture:
CPV beyond kaons and tests of the CKM mechanism

(*CP Violation Studies in 21st Century*)
Backup
\[ D^0(c\bar{u}) \leftrightarrow \bar{D}^0(\bar{c}u) \] oscillation

1) Measurement of mixing induced interference effects in the time-evolution of neutral D meson decays (starting as \( D^0 \) at \( t=0 \)):

**Wrong-sign (WS)** (Doubly-Cabibbo-Suppressed-Decays (DCS) vs Right-sign (RS) (Cabibbo Favored) CF)

**WS/RS ratio**

\[
R(t/\tau) \approx R_D + \sqrt{R_D} y'(t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2.
\]

\[
x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}
\]

\[
y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}
\]

2) measurement of D lifetime in CP eigenstates (e.g. \( D \to K^-K^+ \) (CP even final state) vs \( D \to K^-\pi^+ \) (mixed CP state)

3) Multibody states (e.g. \( D^0 \to K_s\pi^+\pi^- \) (mixing of methods 1) & 2) ]

\[ X = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma} \]

\[ y_{CP} = \frac{\tau_{K^+\pi^-}}{\tau_{K^-K^+}} - 1, \]
$D^0 (c\bar{u}) \leftrightarrow \bar{D}^0 (\bar{c}u)$ oscillation

**BaBar**

**Belle:**

**CDF**

(a) *CPV allowed*

(b) *No direct CPV*

(c) *No CPV*

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Exclude No-Mixing at: 3.9 σ (BaBar), 2 σ (Belle), 3.8 σ (CDF), 9.1 σ (LHCb)