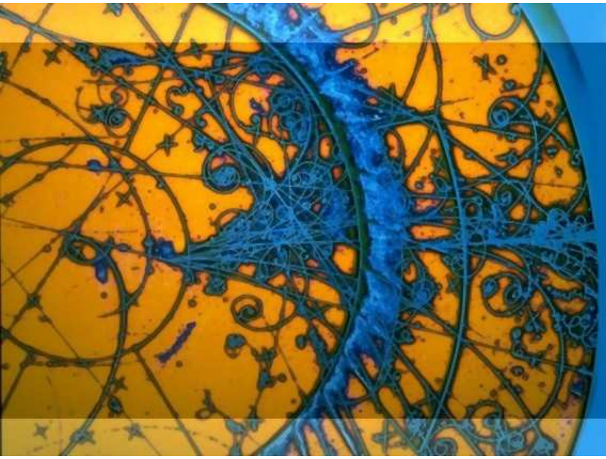
Oral Examination



Observation of CP Violation in Kaon Decays

Igor Senderovich

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Outline

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Discrete Symmetries

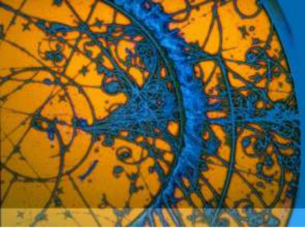
The discrete transformations discussed here have eigenvalues

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

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)

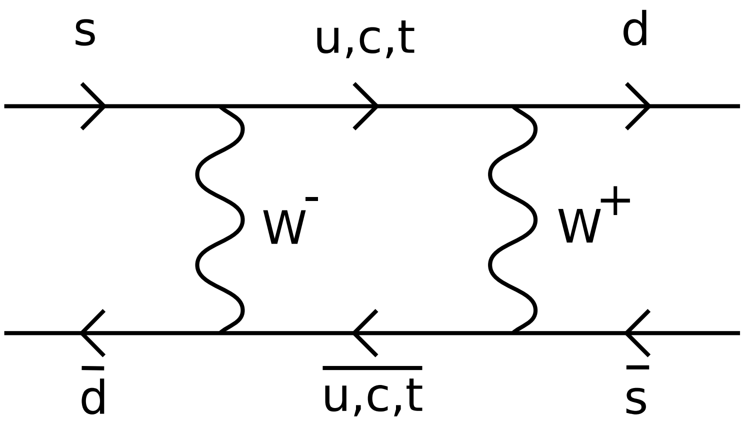
The Kaon System

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. 2π)

Consequence: A neutral Kaon can oscillate into its antiparticle!

Example:



These must not be eigenstates of the full Hamiltonian!

The Kaon System

Mixing Formalism:

Evidently, the strong interaction Hamiltonian*:

$$H_{strong} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix} \qquad \text{eigenstates:} \quad K^0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \overline{K}^0 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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

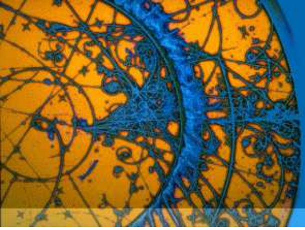
$$H = \begin{pmatrix} M & V \\ V & M \end{pmatrix} \qquad \begin{array}{lll} \text{eigenstates:} & K_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix} & K_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \\ \text{eigenvalues:} & E_1 = M + V & E_2 = M - V \end{array}$$

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.



The Kaon System

Neutral Kaons as states of CP Transformation

Problem: Kaons are not good states of CP: $CP\left(K^0\right) = -\overline{K}^0$

…but the eigenstates of the new Hamiltonian are:

$$K_1 = \tfrac{1}{\sqrt{2}}\left(K^0 - \overline{K}^0\right) \quad \Rightarrow \quad CP\left(K_1\right) = \tfrac{1}{\sqrt{2}}\left(-\overline{K}^0 + K^0\right) = K_1 \quad \left\langle CP \right\rangle = +1$$

$$K_2 = \tfrac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right) \quad \Rightarrow \quad CP\left(K_2\right) = \tfrac{-1}{\sqrt{2}}\left(\overline{K}^0 + K^0\right) = -K_2 \quad \left\langle CP \right\rangle = -1$$

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

$$K_1 \rightarrow 2\pi \quad \left\langle CP \right\rangle_{2\pi} = +1$$

$$K_2 \rightarrow 3\pi \quad \left\langle CP \right\rangle_{3\pi} = -1$$

Is this true or can we find: $K_2 \rightarrow 2\pi \quad \left\langle CP \right\rangle : \quad -1 \rightarrow +1$

The Kaon System

Experimental Perspective

	τ (s)	Main decay modes	Γ_i / Γ	Experimental use
K_1	$\sim 10^{-10}$	$\pi^+\pi^-$	69.2%	← useful for calibration,
		$\pi^0\pi^0$	30.7%	conveniently short lifetime
K_2	$\sim 10^{-8}$	$\pi^+ l^- \nu_l$ or conj. (K_{l3})	67.6%	interesting potential source of CP violation; can *regenerate* K_1
		$3\pi^0$	19.6%	
		$\pi^+\pi^-\pi^0$	12.6%	

Regeneration

$$K_2 = \tfrac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right)$$

$$\overline{K}^0 + p \rightarrow \Lambda^0 + \pi^+$$

$$K^0 + p \rightarrow \Lambda^0 + \underbrace{K^0 + K^+}_{\text{leave little free energy – unlikely!}}$$

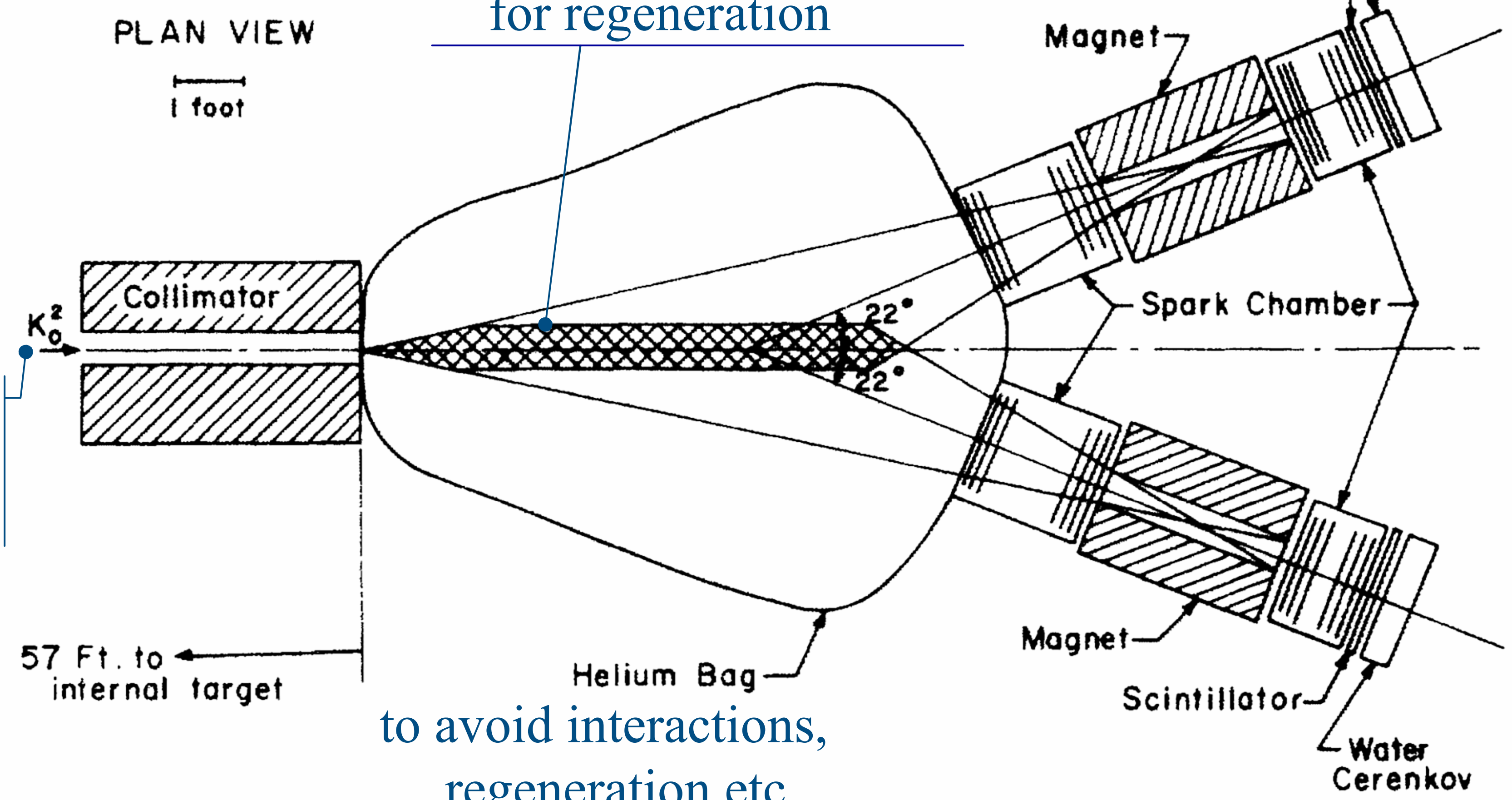
strong interactions: must conserve strangeness

K^0 remains, so K_1 is back! (in superposition with K_2)

Experimental Setup

AGS

Experiment by Cronin, Fitch et. al.



Insertable tungsten target for regeneration

K_1 decayed away by this point

to avoid interactions, regeneration etc.

Data Analysis

2π 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 θ and m distributions of 2π decay and compare with those of K_2 if such decays are found.

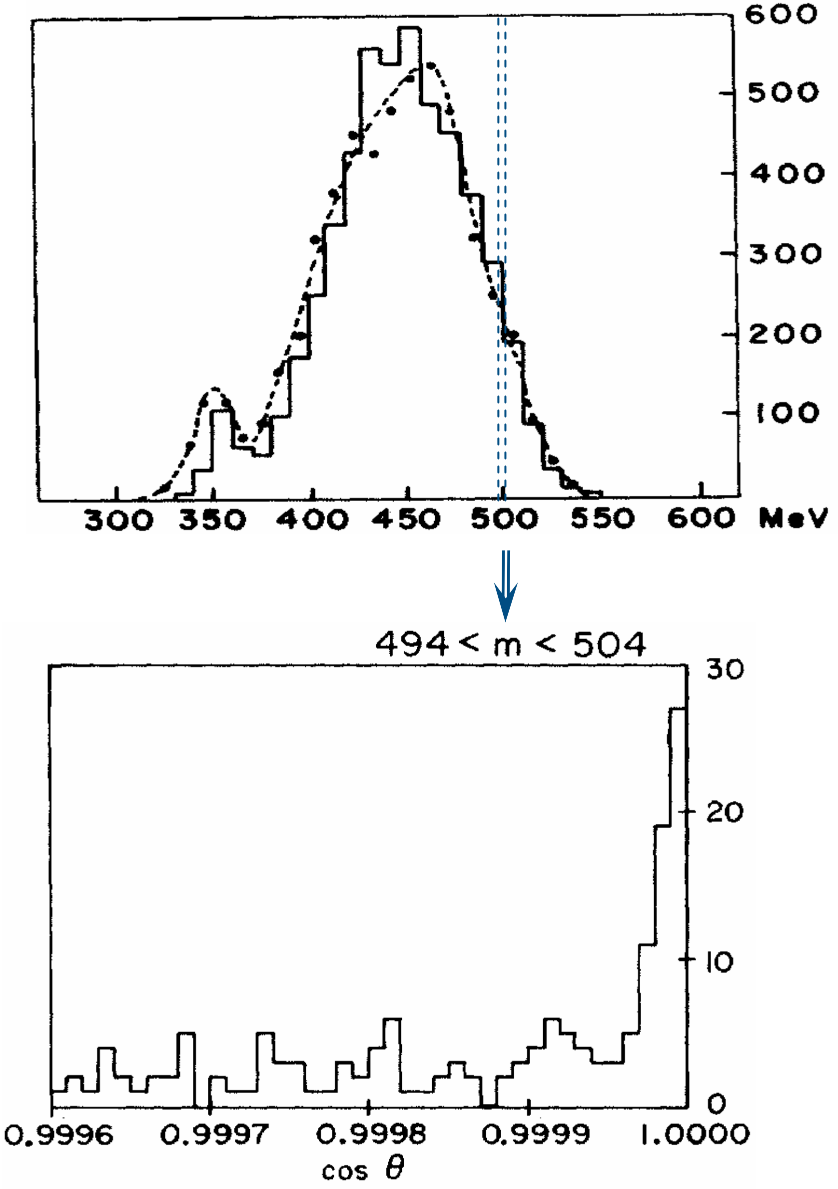
Data Analysis

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 θ distribution (sign of 2-body decay)…

2π decay invariant mass and angle distributions are the same as those from regenerated K_1

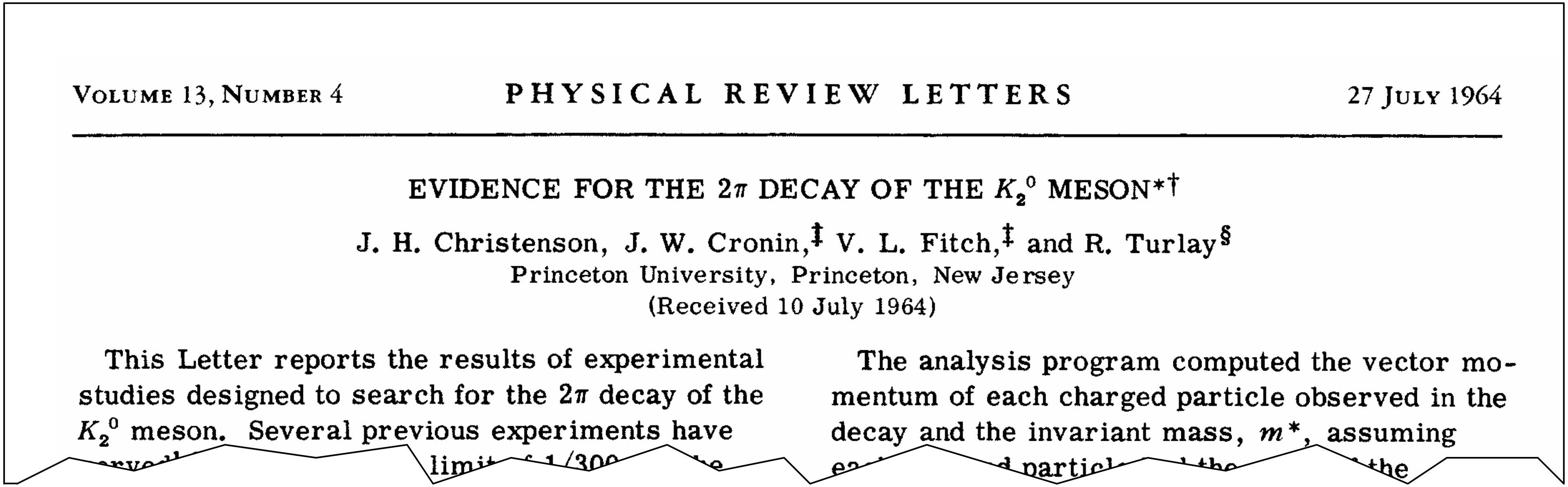
	inv. mass (MeV)	peak angle (mrad)
K_1	498.1±0.4	3.4±0.3
K_2	499.1±0.8	4.0±0.7



Results

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

Reported:



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EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 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

Results

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 ε is the degree of violation. Calculated in the analysis of the original experiment: $|\varepsilon| = 2.3 \times 10^{-3}$

Summary

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.