Discovery of Violations of Fundamental Symmetry Principles in the Decay of Neutral K-mesons

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Seminar on Nobel Prizes in Particle Physics

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Symmetries

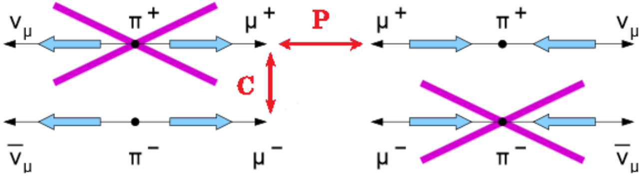
- symmetries play an important role in physics:
  - enabled postulation of undiscovered particles
  - deep connection to conservation laws
- continuous symmetries (Noether's theorem)
- discrete symmetries (represented by operators in QM)
- charge conjugation C: $X \rightarrow \overline{X}$
- parity transformation P: $\vec{r} \rightarrow -\vec{r}$
- time reversal symmetry T: $t \rightarrow -t$
- Pauli & Lüders 1955:

CPT-theorem

Physical phenomena are invariant under combined action of C, P & T.

The path to the discovery of CP violation

- for a long time also separate C-, P- & T-symmetry were assumed to be valid
- Until 1956: Lee & Yang postulated C- & P-violation in the weak interaction
- Experimental confirmation for C- & P-violation by Wu in 1957
- Nobel Prize 1957 awarded to Lee and Yang



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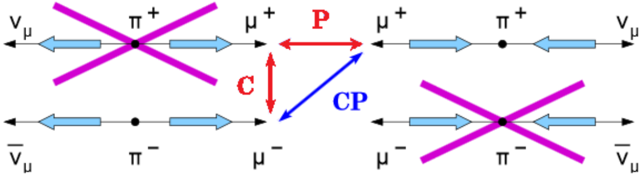


- Landau 1957: violations of C and P compensate each other $\rightarrow$ apparent CP-invariance

- **Evidence for CP violation** in the decay of neutral K-mesons observed by James Cronin & Val Fitch in 1964

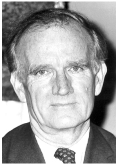
VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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)

- CP violation implies T violation if CPT invariance is assumed
- Sakharov 1967: Conditions for the baryon asymmetry in the early universe (baryogenesis) include CP violation
- 1980 Cronin and Fitch received the Nobel Prize *"for the discovery of violations of fundamental symmetry principles in the decays of neutral K-mesons"*

James Cronin (left)
and
Val Fitch (right)



The neutral kaon system

- **strong eigenstates**: $|K^0\rangle = |d\bar{s}\rangle$ & $|\overline{K}^0\rangle = |s\bar{d}\rangle$
- generated in strong interactions, typical production channels:

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

- neutral kaons decay to hadronic and semi-leptonic final states via weak interaction
- mixing of K^0 & $\overline{K}^0$ via weak interaction
- physical states are superposition of K^0 & $\overline{K}^0$
- K^0 & $\overline{K}^0$ are no eigenstates of CP:

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

CP eigenstates

- **CP eigenstates** are linear combinations of the strong eigenstates:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right), \qquad CP\,|K_1\rangle = +\,|K_1\rangle \qquad \text{"CP even"}$$

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

- for the final states of neutral kaon **decays to pions** one finds:

$$\text{e.g. for } K^0 \to \pi^0\pi^0 \quad J^P : 0^- \to 0^-0^- \Rightarrow L = 0$$

$$CP\,|\pi^0\pi^0\rangle = P\,|\pi^0\pi^0\rangle = (-1)^2(-1)^L = +\,|\pi^0\pi^0\rangle$$

From similar arguments: $CP\,|\pi\pi\rangle = +\,|\pi\pi\rangle$ CP even

$CP\,|\pi\pi\pi\rangle = -\,|\pi\pi\pi\rangle$ CP odd

- assuming CP invariance in the decays thus yields:

CP even: $K_1 \to \pi\pi\,,$ $\quad K_1 \not\to \pi\pi\pi$

CP odd: $K_2 \to \pi\pi\pi\,,$ $\quad K_2 \not\to \pi\pi$

- expect large difference in lifetimes:

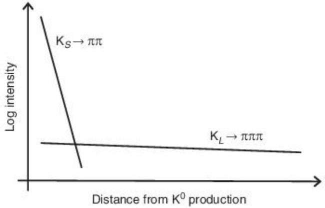
$$m_K - 2m_\pi \approx 220 MeV \gg m_K - 3m_\pi \approx 80 MeV \quad \Rightarrow \quad \tau_1 \ll \tau_2$$

- indeed a short-lived and a long-lived particle K_S & K_L were observed in experiment, **before the discovery of CPV** it was thus natural to identify:

$$|K_S\rangle = |K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}^0\rangle\right)$$

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

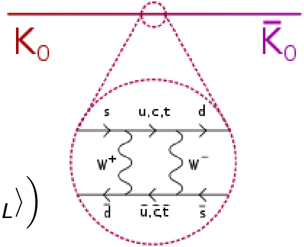
$$\tau_S = 0.9 \cdot 10^{-10} s, \qquad \tau_L = 0.5 \cdot 10^{-7} s$$



tiny mass difference: $m_S \approx m_L \approx 498 MeV$, $\quad \frac{\Delta m}{m} \approx 7 \cdot 10^{-15}$

(Angelopoulos et. al. 2001)

Meson oscillations (assuming CP invariance)



- $K^0 \leftrightarrow \overline{K}^0$-mixing arises from box-diagrams
- WF for production of a K^0 at $t = 0$:

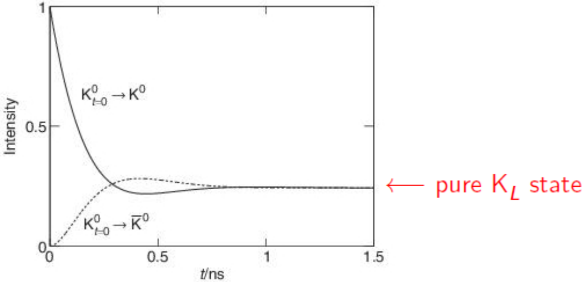
$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}\left(e^{-\frac{t}{2\tau_S}+im_S t}|K_S\rangle + e^{-\frac{t}{2\tau_L}+im_L t}|K_L\rangle\right)$$

- probabilities to be in state K^0 or $\overline{K}^0$ after time t:

$$P(K^0_{t=0} \rightarrow K^0) = |\langle K^0|\psi(t)\rangle|^2 = \frac{1}{4}\left[e^{-t/\tau_S} + e^{-t/\tau_L} + 2cos(\Delta m t)e^{-t/2(\tau_S+\tau_L)}\right]$$

$$P(K^0_{t=0} \rightarrow \overline{K}^0) = |\langle \overline{K}^0|\psi(t)\rangle|^2 = \frac{1}{4}\left[e^{-t/\tau_S} + e^{-t/\tau_L} - 2cos(\Delta m t)e^{-t/2(\tau_S+\tau_L)}\right]$$

Meson oscillations (assuming CP invariance)



- probabilities to be in state K^0 or $\overline{K}^0$ after time t:

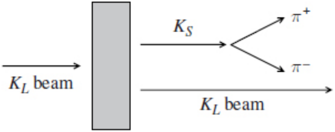
$$P(K^0_{t=0} \to K^0) = |\langle K^0|\psi(t)\rangle|^2 = \frac{1}{4}\left[e^{-t/\tau_S} + e^{-t/\tau_L} + 2cos(\Delta m t)e^{-t/2(\tau_S+\tau_L)}\right]$$

$$P(K^0_{t=0} \to \overline{K}^0) = |\langle \overline{K}^0|\psi(t)\rangle|^2 = \frac{1}{4}\left[e^{-t/\tau_S} + e^{-t/\tau_L} - 2cos(\Delta m t)e^{-t/2(\tau_S+\tau_L)}\right]$$

Regeneration

- $K^0(S=+1)$ and $\overline{K}^0(S=-1)$ interact differently with nuclear matter due to their opposite strangeness
- K^0 only scatters (quasi-)elastically with nucleons:

$$K^0 + N \to K^0 + N^{(*)}$$



- $\overline{K}^0$ can also excite hyperons or resonances thereof:

$$\overline{K}^0[s\bar{d}] + N[uud/udd] \to \pi^0[d\bar{d}] + \Lambda/\Sigma/Y^*[suu/sud]$$

$\Rightarrow$ much stronger absorption of $\overline{K}^0$

Regeneration

Production of K_S as a K_L-beam traverses nuclear matter.

- coherent regeneration: K_S generated in forward direction have identical momentum and phase as incident K_L

The Cronin-Fitch-experiment

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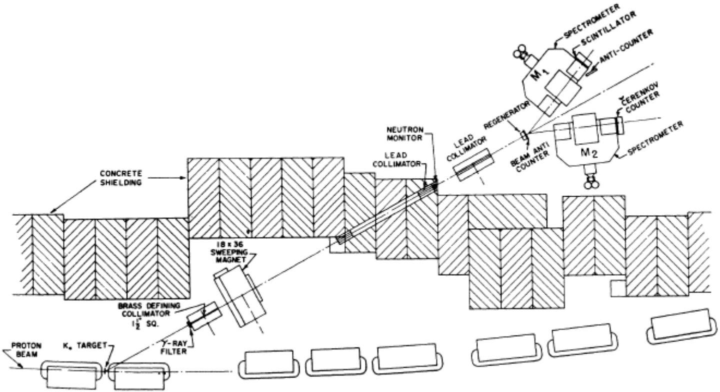
- located at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory
- mainly intended for study of regeneration in neutral kaons
- advent of spark chamber detectors enabled a new level of precision

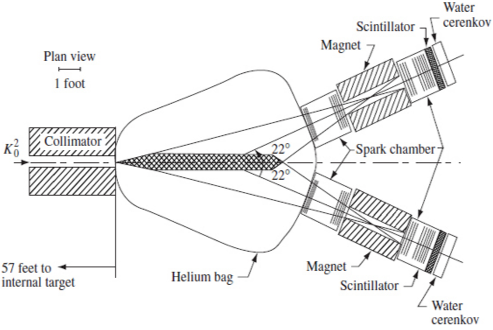
Experimental setup



- K^0 beam produced by bombarding a Be-target with 30GeV-protons from AGS
- after freely propagating 57 feet ($\sim$17.4m) the initial K^0-beam has become purely K_L

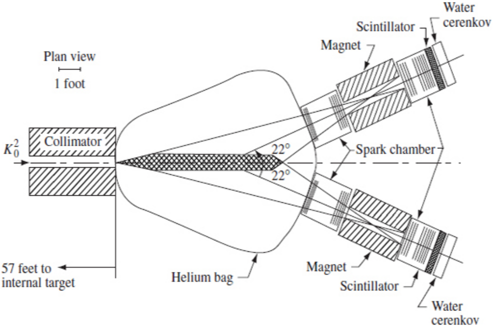
Experimental Setup

- 2 modes of operation
- detection of charged decay products in 2 spectrometers
- spark chambers triggered on coincidence between both spectrometer arms
- analysis program yields 3-momenta $\vec{p}_1$ and $\vec{p}_2$ of detected particles

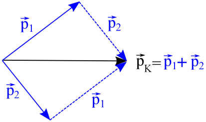


Experimental Setup

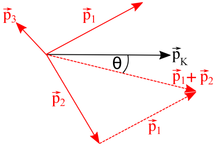
- 2 modes of operation
- detection of charged decay products in 2 spectrometers
- spark chambers triggered on coincidence between both spectrometer arms
- analysis program yields 3-momenta $\vec{p}_1$ and $\vec{p}_2$ of detected particles
- identification of 2π decays:
  1. via 3-momentum sum $\vec{p}_1 + \vec{p}_2$
  2. by invariant mass $m^* = m_K$?



2π decay:

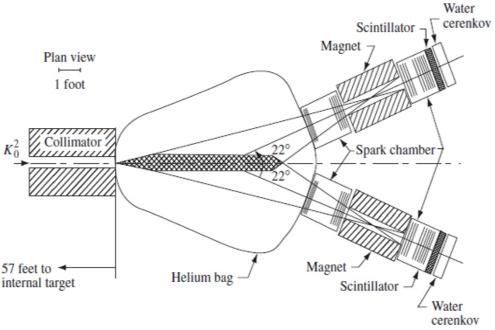


3-body-decay:



Regeneration measurements

- coherent K_S regeneration measurements
  1. calibration for rare CP violating decays $K_L \to \pi\pi$ as these are simulated by the rapid $K_S \to \pi\pi$ decays
  2. important observation: number of detected $K_S \to \pi\pi$ events negligible in He gas

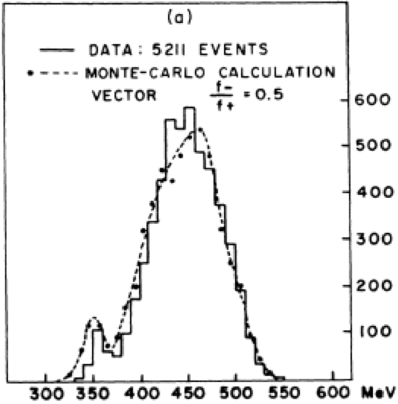


Results - mass distribution of all K_L decays in He gas

- broad peak due to 3-body-decays:

$$K_L \to \pi^+ \ell^- \nu_\ell$$
$$K_L \to \pi^- \ell^+ \overline{\nu}_\ell$$
$$K_L \to \pi^+ \pi^- \pi^0$$

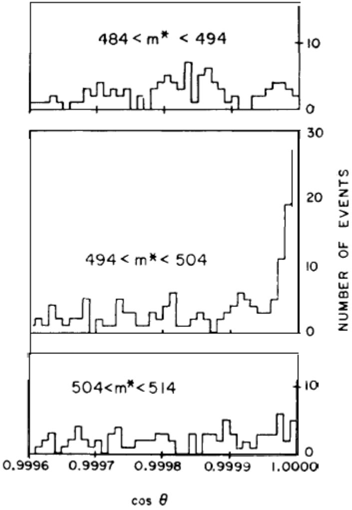
- no signature of decays to two pions recognizable (i.e. no sharp peak around $m^* = m_K \approx 498 MeV$)



Results - angular distribution for different mass ranges

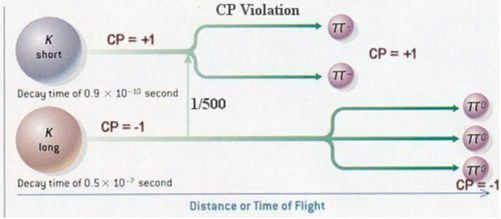
- data from 22700 K_L decays
- uniform background from 3-body-decays
- after background correction: **45±9 events in forward peak** ($cos\theta > 0.9999$) at $m^* \approx m_K$
- as coherent regeneration of K_S negligible in He, these 45 events correspond to $K_L \rightarrow \pi^+\pi^-$ decays

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



CP violation

- we identified $|K_S\rangle = |K_1\rangle$ & $|K_L\rangle = |K_2\rangle$



Assuming CP invariance in decay, we only have:
$K_1 \to \pi\pi \quad (CP = +1)$
$K_2 \to \pi\pi\pi \quad (CP = -1)$

- conclusion: observation of $K_L \to \pi^+\pi^-$ events implies that K_L is not a pure CP-eigenstate $\Rightarrow$ **(indirect) CP violation**!
- The actual **physical states** are then given by:

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_2\rangle + \epsilon\,|K_1\rangle\right) \approx |K_2\rangle$$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_1\rangle + \epsilon\,|K_2\rangle\right) \approx |K_1\rangle$$

with $\epsilon \approx 2.3 \cdot 10^{-3}$

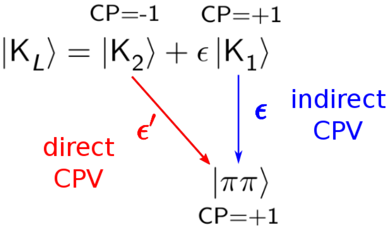
CP violation

- 2nd possibility: CP is violated in the decay (**direct CPV**)

$$|\mathrm{K}_L\rangle = |\mathrm{K}_2\rangle \rightarrow |\pi\pi\rangle$$

$$\text{CP=-1} \rightarrow \text{CP=+1}$$

- also both effects can be realized at the same time:



- direct CPV is quantified by the parameter ϵ'

Theoretical description of CPV

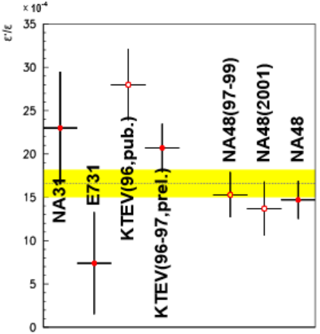
1. superweak theory proposed by Wolfenstein (1964)
   - predicts fifth fundamental interaction: "superweak force" transforming K_L into K_S
   - includes only indirect but **no direct CPV** ($\epsilon' = 0$)
2. Cabbibo-Kobayashi-Maskawa(CKM)-matrix (1973)
   - describes quark mixing due to weak interaction
   - CPV enters via a complex phase factor in CKM-matrix
   - complex phase requires matrix of rank $\geq 3 \Rightarrow$ postulation of 3rd quark generation (NP 2008)
   - **indirect and direct CPV** postulated

$$V_{CKM} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $c_{12} = cos(\theta_{12}), s_{12} = sin(\theta_{12}), \ldots$

Search for direct CP violation

$$\Re\left(\frac{\epsilon'}{\epsilon}\right) \approx \frac{1}{6}\left(1 - \frac{\left|\frac{\Gamma(K_L\to\pi^0\pi^0)}{\Gamma(K_S\to\pi^0\pi^0)}\right|^2}{\left|\frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_S\to\pi^+\pi^-)}\right|^2}\right)$$



- two generations of experiments gave definite results:
  - at CERN: NA31 followed by NA48
  - at FNAL: E731 followed by KTeV
- first **proof of direct CPV** by NA31 in 1993: $\Re\left(\frac{\epsilon'}{\epsilon}\right) = (23 \pm 6.5)\cdot 10^{-4}$
- average from these experiments: $\Re\left(\frac{\epsilon'}{\epsilon}\right) = (16.7 \pm 1.6)\cdot 10^{-4}$
- these measurements ruled out the superweak theory as complete description of CPV while confirming the predictions of the CKM-formalism!

Recent studies of CPV

- current PDG values for CPV parameters in K-system:

$$|\epsilon| = (2.228 \pm 0.011) \cdot 10^{-3}$$

$$\Re\left(\frac{\epsilon'}{\epsilon}\right) = (1.65 \pm 0.26) \cdot 10^{-3}$$

- CPV was also observed for D- & B-mesons
- current research mainly focused on CPV in B-system as the large mass difference between B^0 & $\overline{B}^0$ yields strong interference effects between direct and indirect CP violation
- huge experimental efforts at B-factories and LHCb

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Figure sources

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