THE NEUTRAL KAON SYSTEM: DISCOVERY OF THE K_2 AND **CP** VIOLATION

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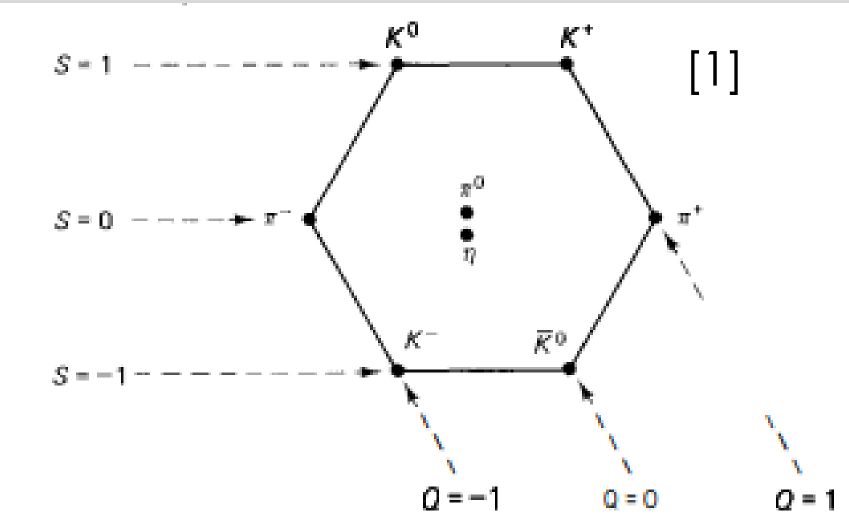
STRANGENESS

- Predicted by Gell-Mann, Pais and Nishijima to explain why relatively high mass particles such as the Kaon decay more slowly then expected.
- One of 6 quark flavours. A strange quark has a strangeness of -1, an anti-strange quark carries a strangeness of -1.
- Conserved in the strong and electromagnetic interactions but not in the weak.

THE NEUTRAL KAON SYSTEM



The meson octet

- Comes in two forms the K^0 and the $\bar{K}^0$.
  - The K^0 is part of the isospin doublet (K^0, K^+)
  - The $\bar{K}^0$ is part of the isospin doublet $(\bar{K}^0, K^-)$
- The quark contents of the K^0 and $\bar{K}^0$ are $d\bar{s}$ and $s\bar{d}$ respectively.
  - K^0 has strangeness 1
  - $\bar{K}^0$ has strangeness -1
  - They have a mass of 497.6 MeV/c^2 [2]

PARITY

- A transformation under the parity operator **P** switches a spatial coordinate between **positive** and **negative**, like mirroring.
- Parity symmetry is valid for strong and electromagnetic processes, but is **violated** when the **weak** force is introduced.
- Violation is illustrated through neutrinos produced from pion decays; **all neutrinos are left handed, whilst all antineutrinos are right handed**.

CHARGE CONJUGATION

- When applied to particles, the charge conjugation operator **C** will switch between **particles** and their **antiparticles**.
- The symmetry of charge conjugation is also broken by **weak interactions** – and again this can be seen in neutrinos.
- Combining **CP** operators solves this issue for neutrinos and creates a new symmetry, however this was found to be **violated by the decay of Kaons.**

STRONG AND WEAK INTERACTION EIGENSTATES

- Strong and weak eigenstates are different.
  - The eigenstates of the strong interaction are those of strangeness
  - The eigenstates of the weak interaction are not those of strangeness
    - Strangeness is not conserved in the weak interaction
- The eigenstates of the weak interaction are (approximately) those of **CP** (charge conjugation and parity)

STRONG AND WEAK INTERACTION EIGENSTATES

- Both the K^0 and the $\overline{K}^0$ decay into $\pi^-\pi^+$ and $\pi^-\pi^+\pi^0$ [4]
  - Both these reactions violate strangeness conservation
  - The reaction must be due to weak decay

- In order to explain this decay we must form eigenstates of the weak interaction.
  - $|K^0\rangle$ and $|\overline{K}^0\rangle$ are the eigenstates of the strong interaction
  - Eigenstates of the weak interaction can be formed through linear combination of the strong eigenstates

STRONG AND WEAK INTERACTION EIGENSTATES

- $K_1 = \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle)$, **CP** Value = 1
- $K_2 = \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle)$, **CP** Value = -1

- These are the eigenstates of **CP**
  - The K^0 and $\overline{K}^0$ particles can be thought of as a mix of these two weak eigenstates[4].

STRONG AND WEAK INTERACTION EIGENSTATES

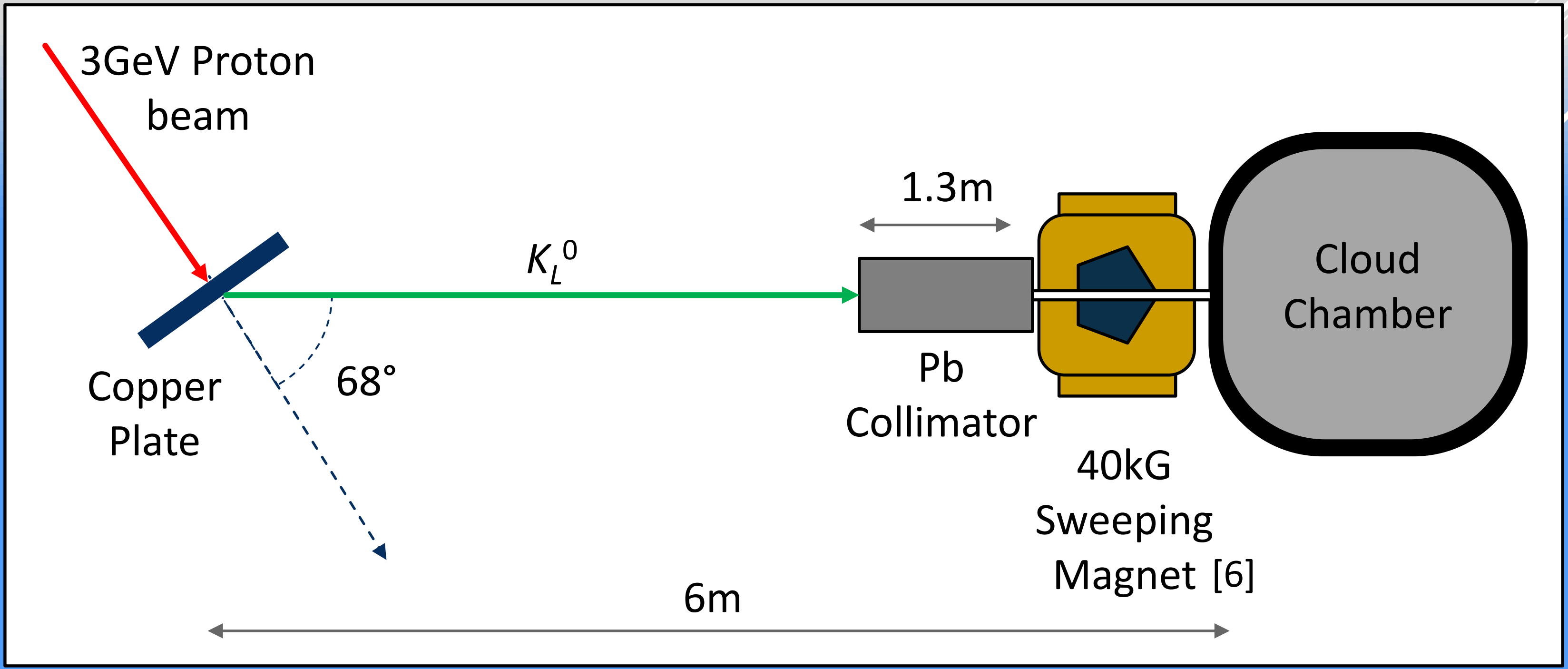
- For the $K^0 \rightarrow \pi^-\pi^+$and $\bar{K}^0 \rightarrow \pi^-\pi^+$ reactions, the $\pi^-\pi^+$ have zero angular momentum[1].
- Parity is therefore, $\boldsymbol{P} = (-1)^L = 1.$
- Charge conjugation is also 1.
  - In order to conserve **CP** the K_1 undergoes this decay

- For the $K^0 \rightarrow \pi^-\pi^0\pi^+$ and $\bar{K}^0 \rightarrow \pi^-\pi^+\pi^0$ reactions, the **CP** value of the $\pi^0 = -1$ and so the K_2 must undergo this decay[4].

- The $\pi^-\pi^+$ reaction is much quicker as there is much more phase space available for this reaction. The K_2 component has a 600 times longer lifetime than the K_1[4].

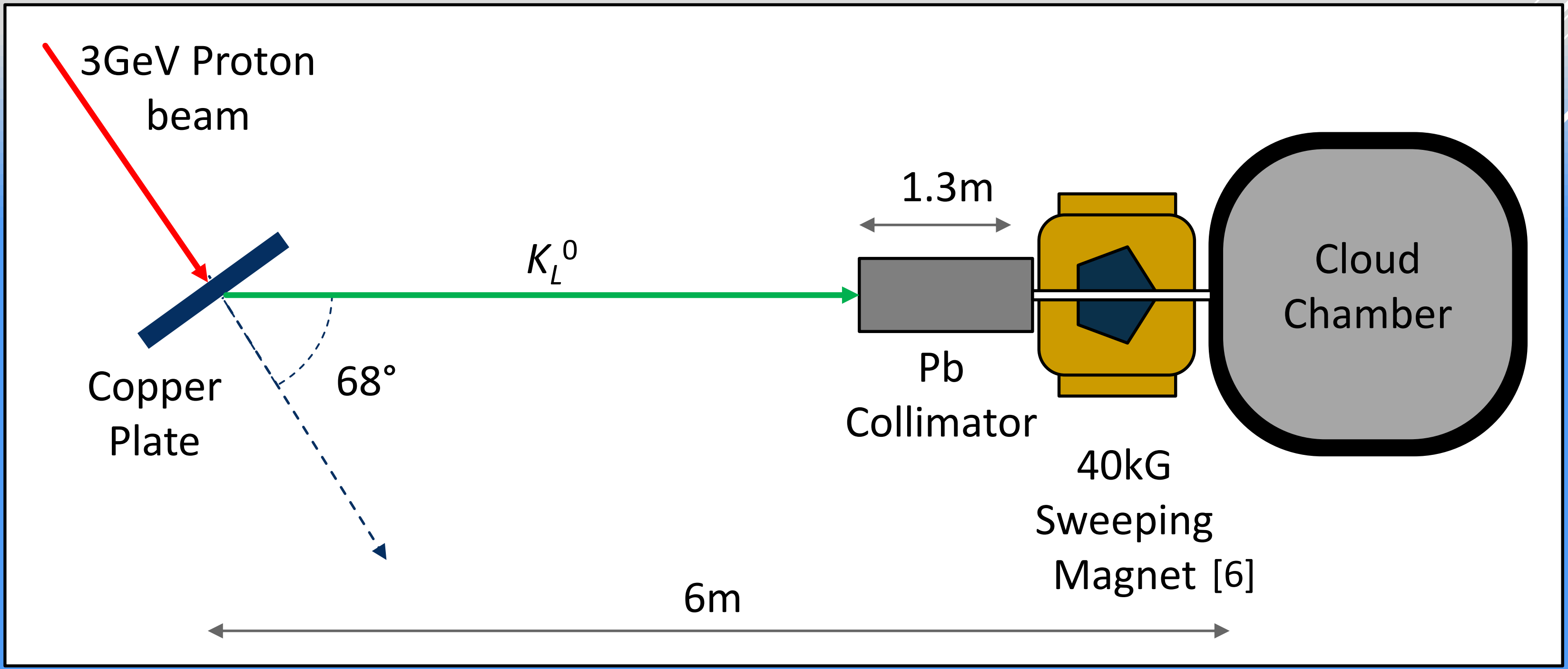
INITIAL K_L DISCOVERY: COSMOTRON 1956

- $K_L = K_2$ if **CP** symmetry is not violated.
- K_L is the physically detected particle – not a pure **CP** eigenstate – called indirect **CP** mixing.
- Experiment performed by **Lande , Booth et al.** at the Brookhaven Cosmotron, US.
- 3 GeV proton beam incident at 68° to copper plate, produces **neutral radiation**[5].
- 1.5 in Pb filter placed before collimator to **reduce γ-ray flux.**



INITIAL K_L DISCOVERY: COSMOTRON 1956

- **Charged particles removed** from scattered beam by 4 ft lead collimator and 40 kG sweeping magnet.
- **Cloud chamber** with 90% He and 10% Ar used.
- Chamber placed **6m** from copper plate, over 100 lifetimes of K_S and Λ_0 particles.

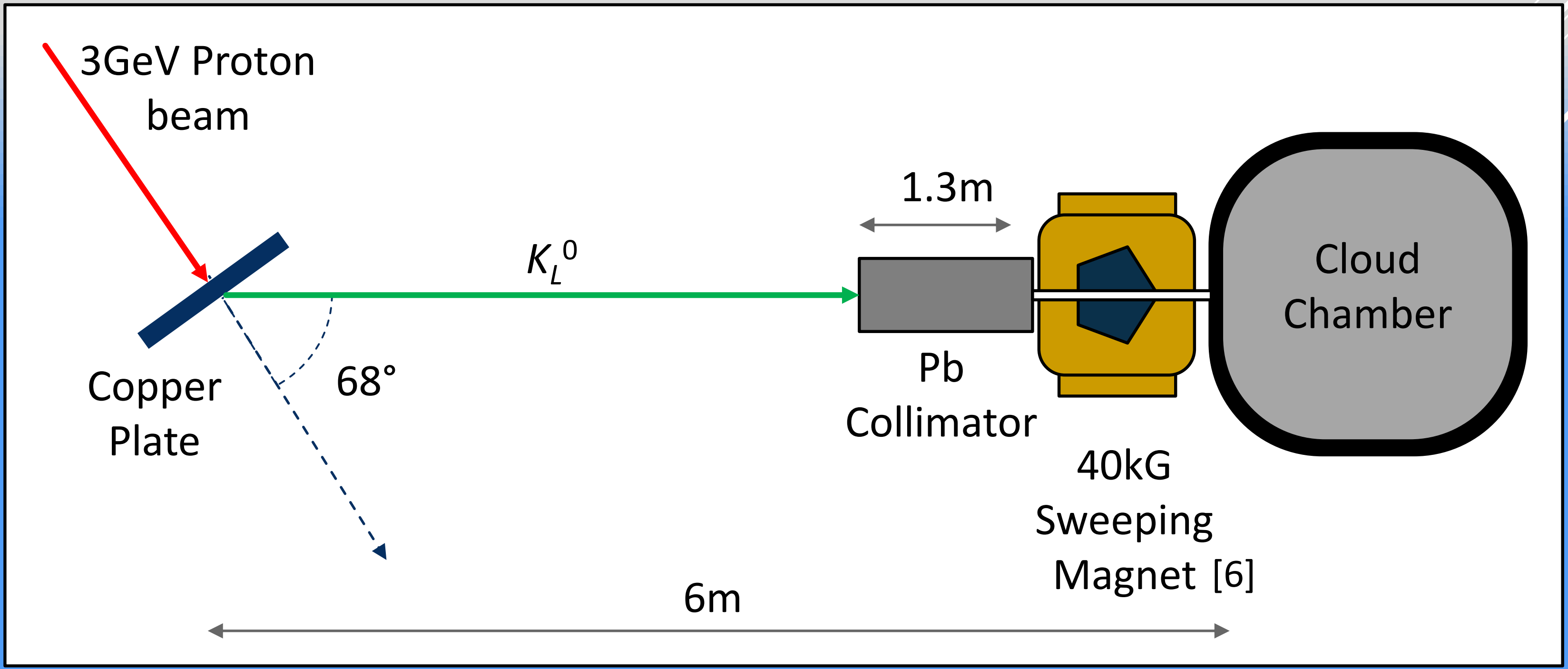


INITIAL K_L DISCOVERY: COSMOTRON 1956

- Other possible decays **discounted**:
- $n \rightarrow \pi^+\pi^-$
- $\pi^0 \rightarrow e^+e^-\gamma$
- $\gamma \rightarrow e^+e^-$

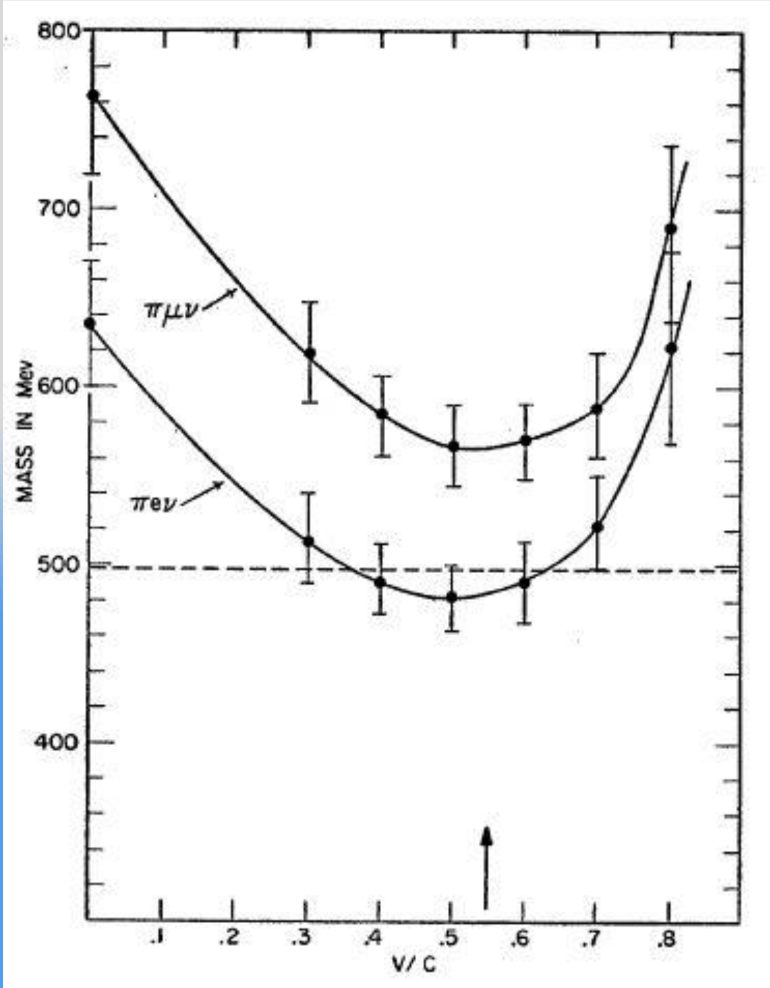
Forked tracks of **three body decay** modes observed - decay products identified as **muons, pions electrons**[5]:

$K_L \rightarrow \pi^{\pm}e^{\mp}\upsilon_e$
$K_L \rightarrow \pi^{\pm}\mu^{\mp}\upsilon_e$
$K_L \rightarrow \pi^{+}\pi^{0}\pi^{-}$



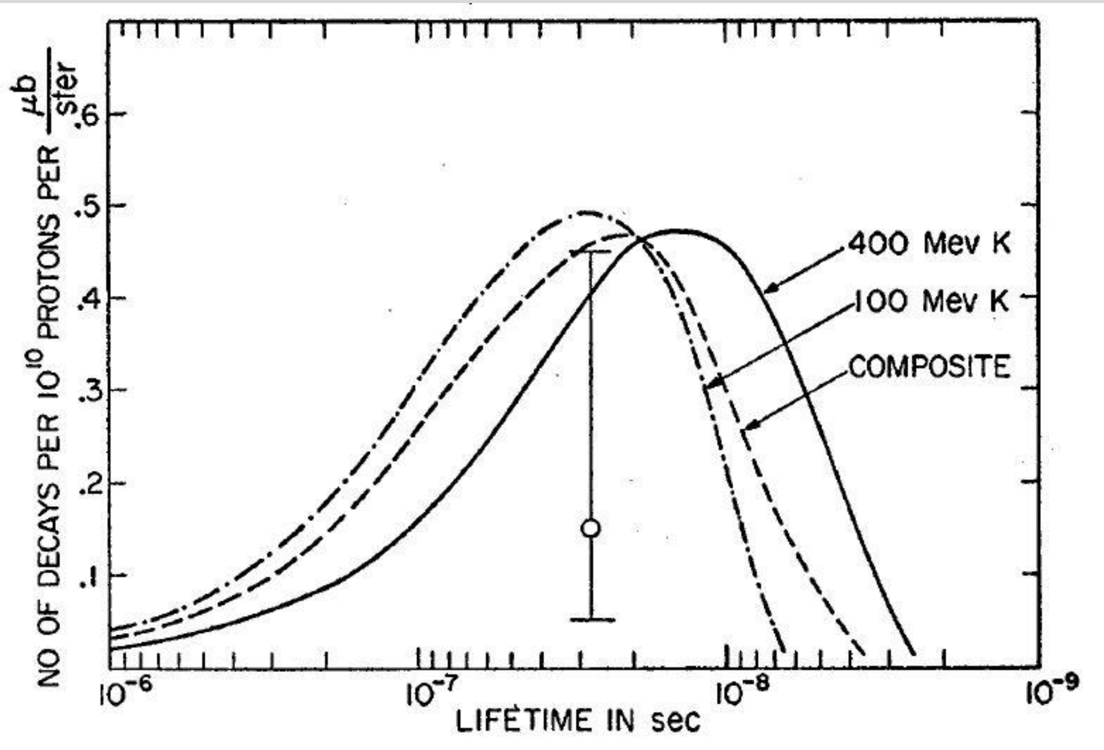
INITIAL K_L DISCOVERY: COSMOTRON 1956

- Variation of the computed incoming particle mass measured as a **function of velocity,** using the kaon decay products.
- Velocity distribution **consistent** with particle of mass around **500 MeV** – almost identical to the charged kaons[5].

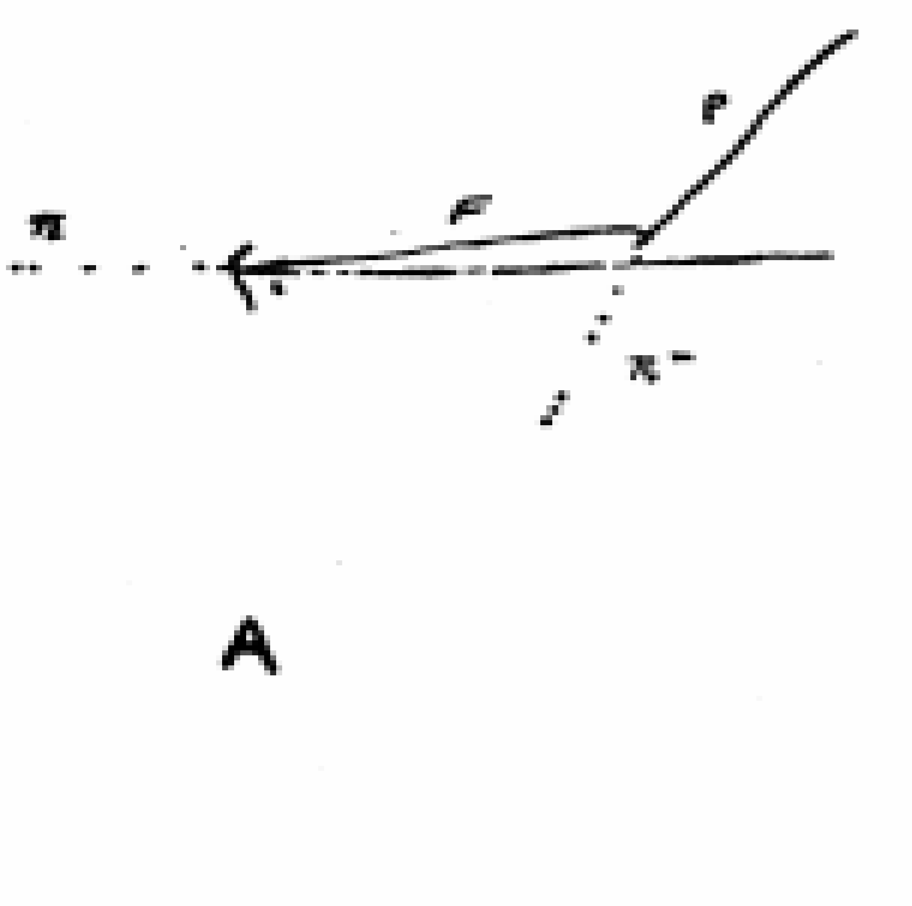


INITIAL K_L DISCOVERY: COSMOTRON 1956

- Plotted detection sensitivity as function of lifetime for a "K" mass particle.
- Lifetime found as **$10^{-9} < \tau < 10^{-6}$ s** via production cross section of decay products.
- Likely closer to **10^{-8} s** as would explain many V^0 decays previously thought to be alternate K_L decays.

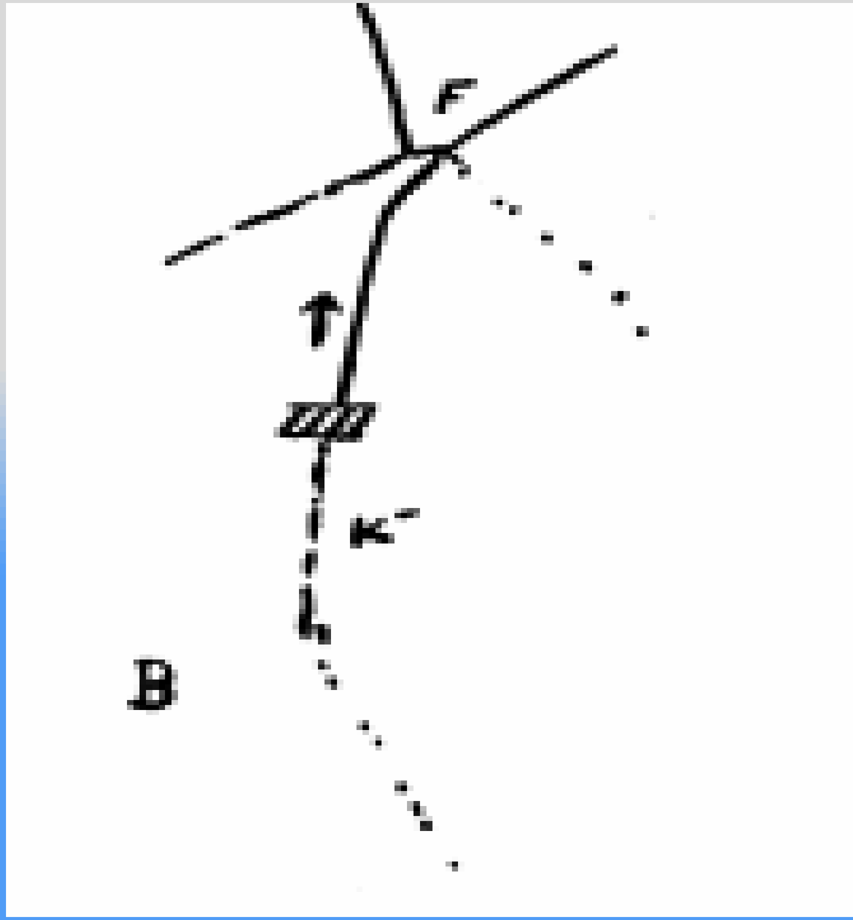


EVIDENCE FOR K_2 IN EMULSION EXPERIMENTS



- In 1956, W. H. Fry, J. Schnepps and M. S. Swami reported 4 unusual events during a search for K^-mesons. They exposed emulsion to a channel of negative particles[7].
- A hyperfragment ${}^4_\Lambda\mathrm{He}$, a π meson and a proton originated from a star. The star was produced by a neutral particle which had to have strangeness.
- Two short recoil tracks are distinguishable.

EVIDENCE FOR K_2 IN EMULSION EXPERIMENTS



- A K^- meson was produced with a low energy electron and a nucleonic particle. The particle which produced this reaction must have strangeness and be neutral.

- The K^- then produced a hyperfragment, a π meson and nucleons from rest.

EVIDENCE FOR K_2 IN EMULSION EXPERIMENTS

- These events could be explained by the nuclear interaction of a neutral unstable particle of the same strangeness as the K^- meson.

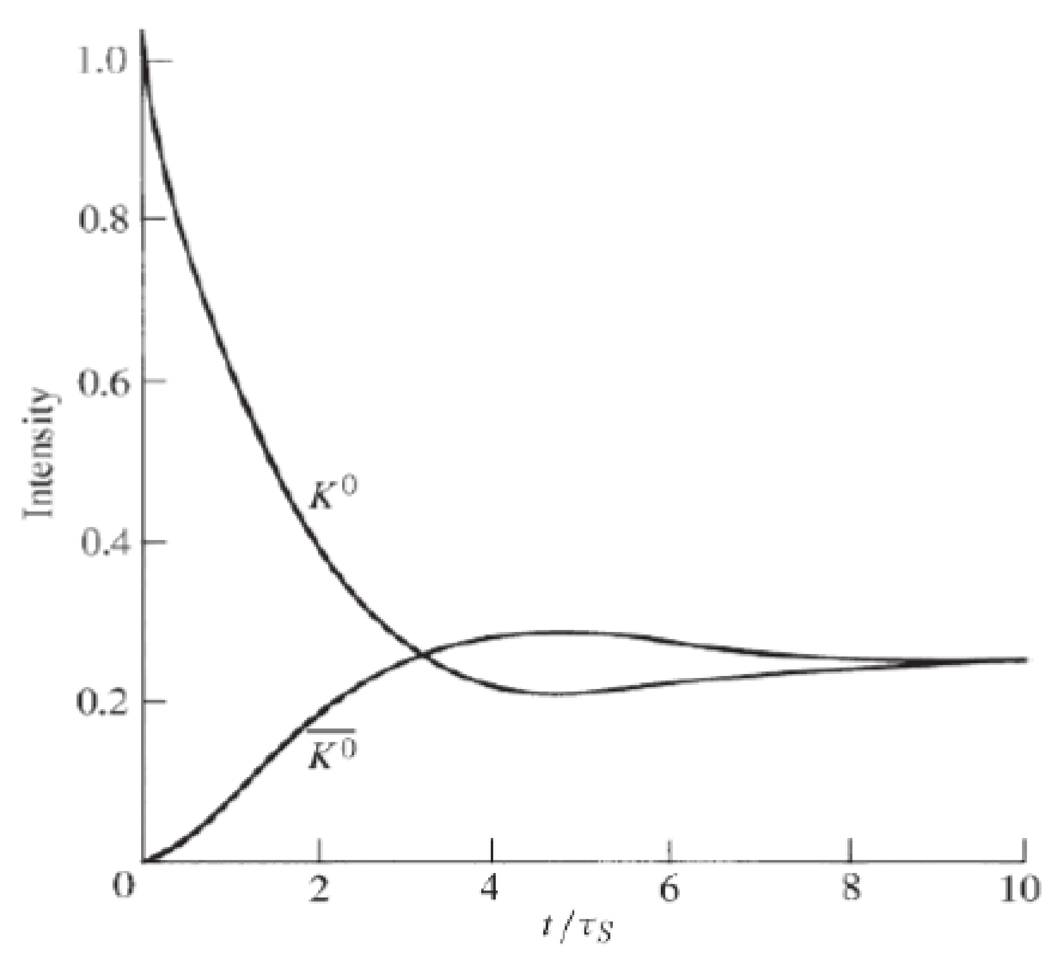
- The total energy in event 2 is too high to be due to a neutral Kaon from the charge exchange of a K^-, this rules out it being a short lived neutral Kaon

- All events can be explained by assuming that long lived neutral kaons were produced with the lifetime of about 10^{-8} s[7].

TRANSFORMATION OF K^0

Report by Lande, Lederman and Chinowsky in 1957 [8]. Neutral kaon beam fired at a helium target produced a final state with negative strangeness, $\Sigma^- pp n \pi^+$ [4].

Beam initially pure K^0 (positive strangeness) as $\overline{K}^0$ can only produced at high energy because there are no baryons with positive strangeness [11]. Suggested transformation between the two neutral kaon states.



OSCILLATIONS OF K^0

If a state is purely K^0 it will oscillate between K^0 and $\bar{K}^0$ while propagating. The amplitude of oscillation can be observed through semileptonic decays.

A semileptonic decay is where a hadron decays via the weak force producing a lepton, its corresponding neutrino and one or more hadrons [10].

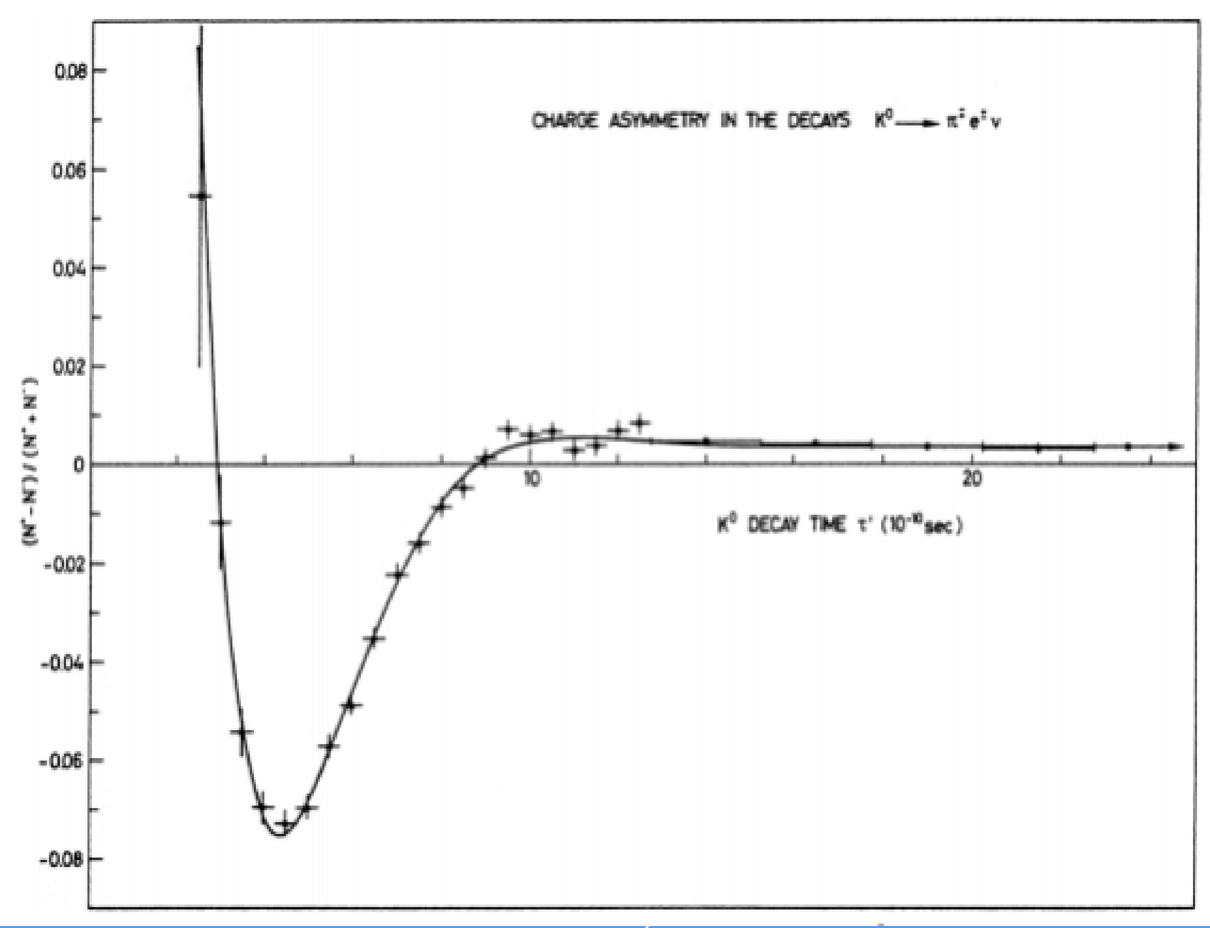
$$I(K^0) = \frac{1}{2}\left(e^{\frac{-im_1\tau-\Gamma_1\tau}{2}} + e^{\frac{-im_2\tau-\Gamma_2}{2}}\right)$$

$$I(\bar{K}^0) = \frac{1}{2}\left(e^{\frac{-im_1\tau-\Gamma_1\tau}{2}} - e^{\frac{-im_2\tau-\Gamma_2}{2}}\right)$$

Amplitude of oscillation equations [14]

OBSERVATION OF K^0 OSCILLATIONS

$$K^0 \rightarrow \pi^- e^+ \upsilon_e$$
$$\bar{K}^0 \rightarrow \pi^+ e^- \bar{\upsilon}_e$$

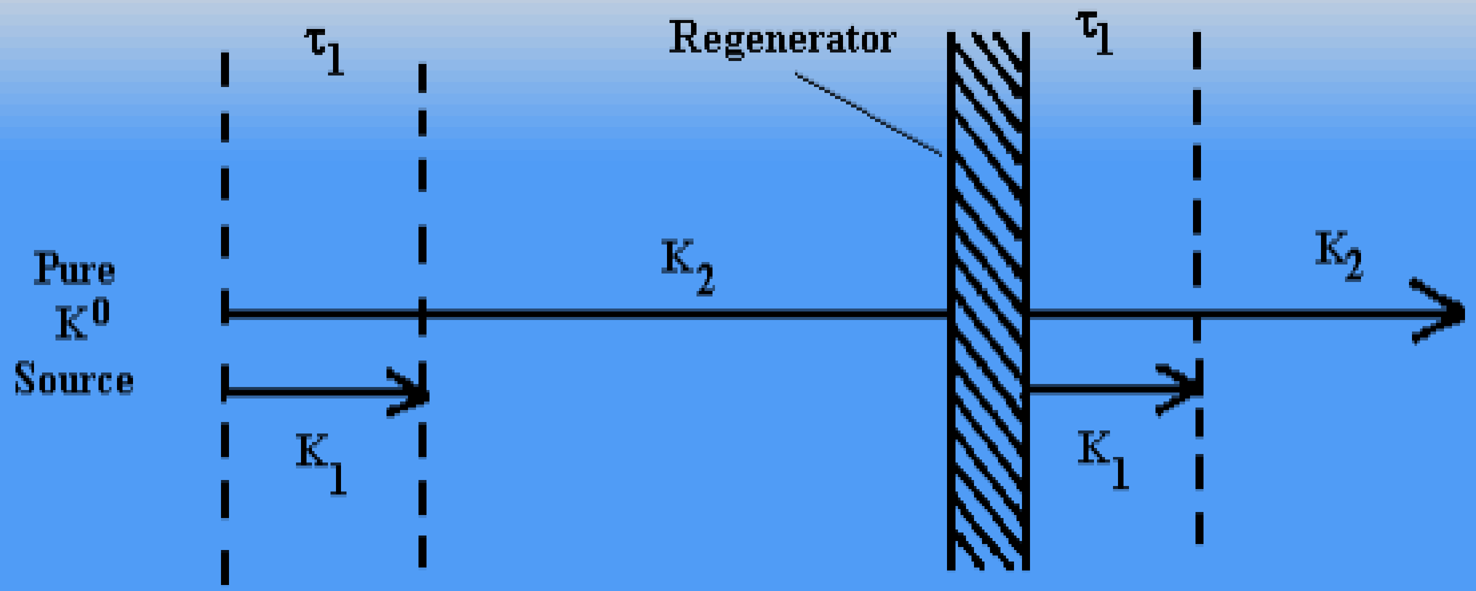


The graph[4] shows the ratio of the difference in positrons to electrons produced to the total number of electrons and positrons plotted against the proper time, τ.

The non-zero asymmetry is a **CP** violating effect.

REGENERATION OF K_1

Decay rate of K_1 is much faster than K_2 so if a neutral kaon beam travels a long distance only K_2 remains. K^0 and $\bar{K}^0$ have different cross-sections so interact differently in matter, known as the “regenerator”. K^0 undergoes elastic scattering with the nuclei whereas the $\bar{K}^0$ produces hyperons, ($\bar{K}^0\, p \rightarrow \Lambda\, \pi^-$). Hence the amplitudes of the neutral kaons oscillations will be different. Therefore, a component of K_1 is reintroduced into the linear superposition’s of K^0 and $\bar{K}^0$ [14].



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

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

MASS DIFFERENCE OF K_1 AND K_2

The oscillations between K^0 and $\bar{K}^0$ occur with frequency Δm, the mass difference between K_1 and K_2. In addition, the amount of K_1 regenerated in matter depends on the mass difference [14].

First attempts to determine this difference were made by Muller in 1960. A neutral kaon beam was generated far enough away from a bubble chamber that only K_2 would remain. K_1 produced would be detected by observing pion pairs that reconstructed to the proper mass [12]. Mass difference was first calculated to be 0.85 [15], but it is now known to be 0.474 [4].

K_2 was determined to be the heavier of the two by scattering neutral kaons with nucleons and observing interference between the K^0 and $\bar{K}^0$ contributions [4].

BACKGROUND/RECAP OF K_S AND K_L

K^0 and $\bar{K}^0$ differ only in strangeness. The weak interaction does not conserve strangeness, and therefore does not distinguish between these two particles. What we actually observe is superposition of eigenstates:

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \qquad |K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

$$CP|K_1\rangle = |K_1\rangle, \quad CP = +1 \qquad CP|K_2\rangle = -|K_2\rangle, \quad CP = -1$$

K_1 is easily able to decay to $\pi^+\pi^-$ which has $\boldsymbol{CP} = 1$. However, K_2 will decay to $\pi^+\pi^0\pi^-$ in order to conserve **CP**. Due to the mass difference in decay products, K_1 will decay much faster and so is shorter lived.

This led to the weak eigenstates of the neutral kaon to be described as K_S (short-lived) and K_L (long-lived). If we could observe K_L decay to $\pi^+\pi^-$, this would be proof of **CP** violation.

CRONIN & FITCH EXPERIMENT – BROOKHAVEN, 1964

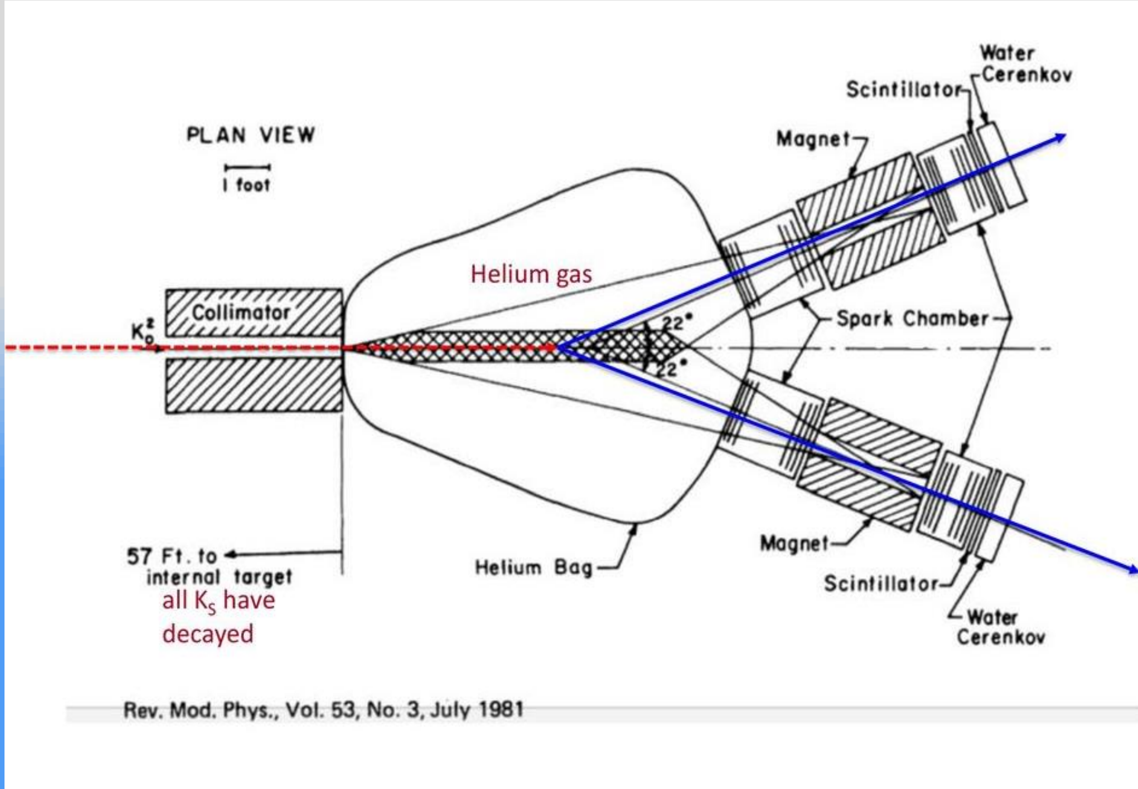
Attempt to observe decay of K_L to $\pi^+\pi^-$

Used a long, 57 ft, beam to produce pure sample of K_L

Decays of K_L were observed inside region of He gas

Used two identical detectors made up of:

- Two spark chambers separated by a magnet - for track delineation and momentum determination
- Scintillation counter - triggered by charged particles
- Cherenkov counter - Cherenkov radiation produced by charged particles allows velocity determination for discriminating π^+/π^- from e^+/e^-



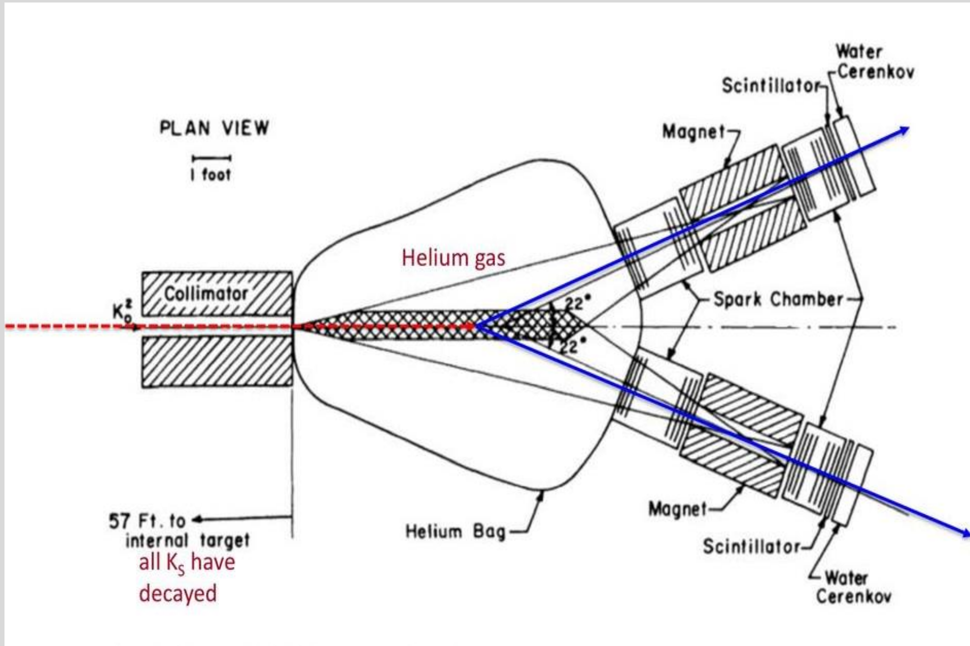
CRONIN & FITCH EXPERIMENT – BROOKHAVEN 1964

Neutral pion decays before reaching the spark chamber, so distinguish between three-body, 3π and two-body, 2π decay using conservation of energy and momentum.

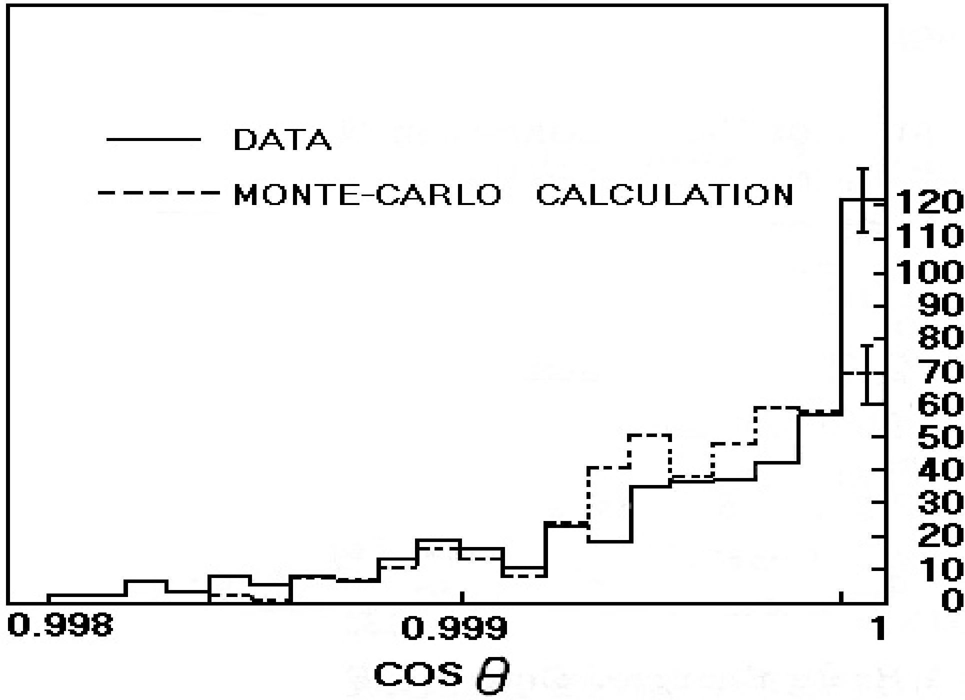
In two-body decay, the sum of the angles of the charged particles from the horizontal (the beam direction), θ, will almost always be zero.

In three-body decay, this sum of angles is very rarely zero.

Cronin and Fitch measured $\cos\theta$ of 22,700 decays and found 45±9 events around $\cos\theta = 1$, around 1 in 500.



Rev. Mod. Phys., Vol. 53, No. 3, July 1981



INDIRECT **CP** VIOLATION

This experiment destroyed hope in the particle physics community of exact **CP** symmetry, but **why did it happen?**

The Cronin-Fitch experiment is an example of **Indirect CP** violation. K_1 and K_2 are eigenstates of **CP**, but are not perfect eigenstates of the weak interaction, which governs how they decay. Likewise, K_S and K_L, the weak eigenstates, are not perfect eigenstates of **CP** but a superposition of $\boldsymbol{CP} = 1$ and $\boldsymbol{CP} = -1$ states. The long-lived weak eigenstate is given by;

$$|K_L\rangle = \frac{1}{\sqrt{1 + |\varepsilon|^2}}(|K_2\rangle + \varepsilon|K_1\rangle)$$

Where $\varepsilon = 2.3 \times 10^{-3}$

DIRECT AND INDIRECT **CP** VIOLATION

Indirect CP violation is when the violation does not occur in the decay, but during the interference of mixing where a small admixture of the opposite **CP** eigenstate decays in a **CP** conserving fashion.

This is in contrast to **direct CP** violation, where the violation occurs within the decay itself and not as a result of the mixing of **CP** eigenstates.

This was not observed until much later. It was initially reported by the NA31 experiment at CERN in 1988, and then confirmed by CERN’s NA48 and Fermilab’s kTeV experiments in 1999. Direct **CP** violation was determined from observations of the relative decay rates of K_S and K_L into neutral and charged pions.

More recent research has focused on observations of B mesons, which have been found to both directly and indirectly violate **CP** during their decays.

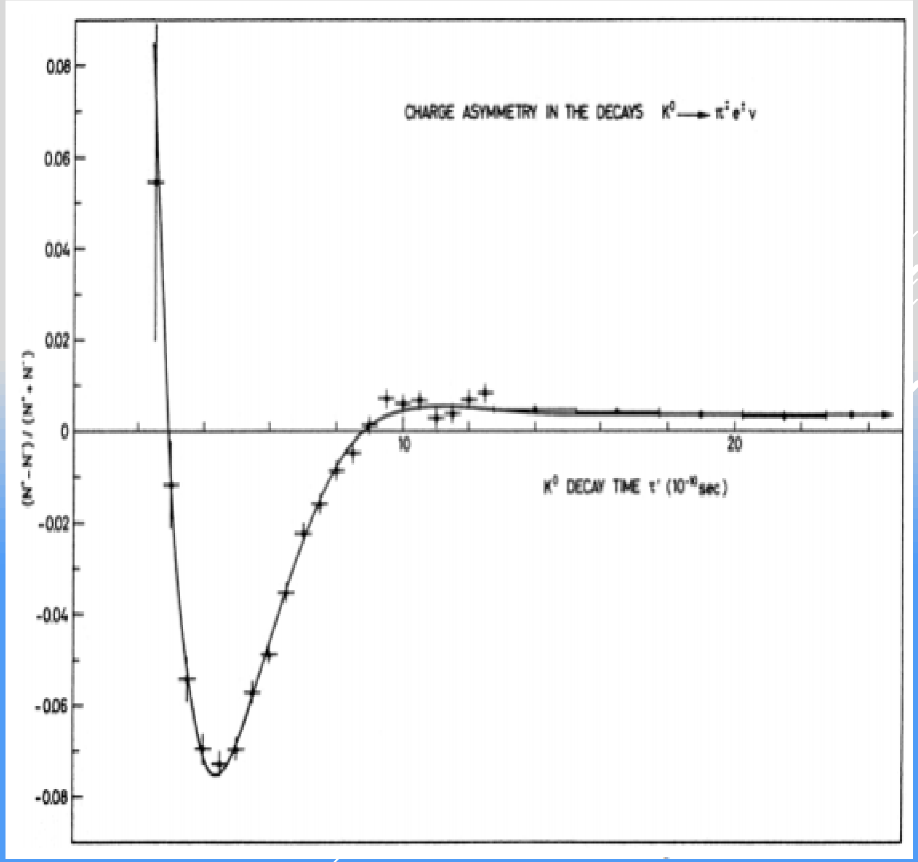
CONSEQUENCES OF **CP** VIOLATION

Consider the semileptonic decays of K_L. Whilst 34% of K_L decays to 3π, 39% decays to:

(a) $\pi^+ + e^- + \bar{\upsilon}_e$ (b) $\pi^- + e^+ + \upsilon_e$

Note that (a) is the **CP** conjugate of (b). Therefore, these decays should occur with even frequency, but that does not happen.

K_L preferentially decays into a positron by a factor of around 3.3×10^{-3} .This is also the first observation of a process seeming to make a distinction between matter and antimatter.



TIME REVERSAL

- **Time reversal symmetry** requires that any process performed one way can also be performed backwards.
- The operator **T** corresponds to the time reversal of any process.
- This is assumed to be violated by weak interactions too, though this is very hard to test.
- So what about combining all **C**, **P** and **T** operators?

CPT THEOREM

- When combined, the **C**, **P** and **T** operators create an **exact symmetry** of any process. This is firmly thought to be a **fundamental law**.
- The **CPT** theorem requires that all particles have equivalent mass to their antiparticles. Experiments measuring this for kaon masses are yet to disprove this.
- The symmetry of **CPT** cannot, as far as we know, be violated by any process.

SUMMARY

- We have described what the **neutral kaon system** is, as well as the experimental evidence for the **short- and long-lived neutral kaons**.
- Discussed the **oscillation** between K^0 and $\overline{K}^0$ as well as the **regeneration** of in K_1 matter.
- Given an overview of **parity**, **charge conjugation** and **CP theorem**.
- Explained how kaon decays show **CP violation**, and introduced **CPT theorem** as an alternative symmetry.

REFERENCES

1. Griffiths, D. Introduction to elementary particles. (WILEY-VCH Verlag GmbH, 2004).

2. Public data group. Meson Particle Listings. *Phys. Letters B*. **592**, 495-850 (2004).

3. Lacoste-Julien, S., 2002, Discovery of CP violation. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.541.7786&rep=rep1&type=pdf

4. Cahn, R., & Goldhaber, G. (2009). *The Experimental Foundations of Particle Physics*. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511609923

5. Lande, K. *et al.*, “Observation of Long lived Neutral V Particles.” *Phys Rev*., **103**. 1901 (1956).

6. InspireNet Synchrotron Neutral Kaon Observation Apparatus (2018) Available at: http://inspirehep.net/record/1635556/plots. [Accessed 08/10/2018]

8. Fry, W. F., Schneps, J. and Swami, M. S., “Evidence for Long-lived Neutral Unstable Particle.” *Phys. Rev*., **103**, 1904 (1956).

9. Lande, K., Lederman, L.M., and Chinowsky, W., 1957 “Report on Long Lived *K*0 Mesons.”*Phys. Rev.*, 104.

10. Dingfelder, J., & Mannel, T., 2016. Leptonic and semileptonic decays of B mesons. *Reviews of Modern Physics*, 88(3), pp.1-58

11. Booth, C., 2017, PHY304 Particle Physics Lecture Series, University of Sheffield.

12. Muller, F., *et al.*, 1960, Regeneration and Mass Difference of Neutral K Mesons. *Phys. Rev. Lett.*, **4**, 418.

13. Lloyd, S. L., 1997, Neutral Kaon Decay Lectures 17 and 18, Elementary Particle Physics

14. D. H. Perkins. Introduction to high energy physics, Cambridge University Press.

15. Good, R. H., 1962, Regeneration of Neutral K Mesons and their Mass Difference, University of California, Berkeley CA