2. Phenomenology of the neutral Kaon system

Neutral Kaons: $K^0(d\bar{s})$ $\bar{K}^0(\bar{d}s)$

K_S^0 K_L^0

Strangeness content?

$m_{K^0} = 498\,\text{MeV}$

$\tau_{K_s} = 90\,\text{ps}$ $\tau_{K_L} \approx 52\,\text{ns}$

With the additive quantum number S, anti-particles must have opposite strangeness to that of particles: 2 neutral Kaons with S=±1 (non-sell conjugated)
(like the π^0 and γ)

Question by Fermi during a M.Gell-Mann seminar in 1954:

If the 2 neutral kaons decay both to the same final state $\overset{(-)}{K^0} \to \pi^+\pi^-$ how can they be distinguished?

2.1 K^0 and $\bar{K}^0$: a 2-state system

a) Prediction of 2 neutral self-conjugated neutral Kaons

M. Gell-Mann, A. Pais 1955

Since the 2π-state from the K^0 decay cannot be distinguished from the 2π-state from $\bar{K}^0$ there must be a transition between the two-states possible:

$$K^0 \leftrightarrow 2\pi \leftrightarrow \bar{K}^0$$

⟹ $K^0, \bar{K}^0$ cannot be the physical states propagating freely through the vacuum.

If CP is conserved (see later) the CP-symmetry can be used to characterize the two physical (propagating) states:

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

$$\text{CP}\left|K_1\right\rangle = +\left|K_1\right\rangle \qquad \text{CP}\left|K_2\right\rangle = -\left|K_2\right\rangle$$

} Self-conjugated

(with appropriate choices of the CP phases of $K^0, \bar{K}^0$)

Masses and lifetimes of K_1 and K_2 are in general different: Δm and $\Delta\Gamma$

While $K^0, \bar{K}^0$ are constraint by CPT to have the same masses and lifetimes K_1 and K_2 are not.

Remark: If CP is violated, the corresponding physical states K_1 and K_2 can still be defined as above, they are however no CP eigenstates anymore!

Gell-Mann and Pais predicted 2 neutral self-conjugated physical states which are, CP eigenstates and which have different masses and lifetimes (assuming CP is conserved).

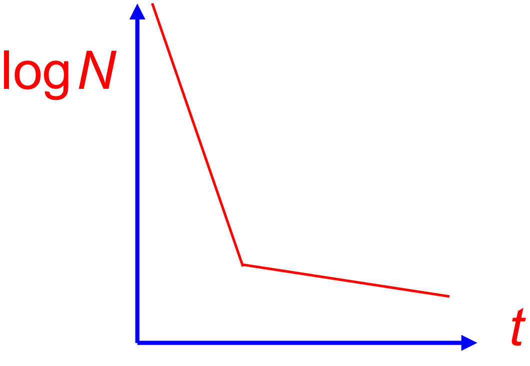
Discovery of the K_L (K_2) at the cosmotron in 1957: $\tau \approx 5.2 \times 10^{-8}$ s

The observed lifetime difference between the two neutral states is the result of the phase space difference of the allowed decays:

$$K_s\ (K_1, \mathrm{CP}=+1) \rightarrow \pi^+\pi^-, \pi^0\pi^0\ (\mathrm{CP}=+1)$$

$$K_L\ (K_2, \mathrm{CP}=-1) \rightarrow \underbrace{\pi^{+,0}\pi^{-,0}\pi^0}\ (\mathrm{CP}=-1)$$

Little phase space left ⇒ long lifetime



b) Another prediction: $K^0\bar{K}^0$-oscillation (Gell-Mann & Pais)

Oscillation between K^0 and $\bar{K}^0$ as function of t:
Due to the mixing $K^0 \leftrightarrow 2\pi \leftrightarrow \bar{K}^0$ the K^0 and $\bar{K}^0$ should not exhibit a pure exponential decay but an oscillatory behavior.

When propagating through the vacuum the two strangeness states are the two components of a 2-state system:

$$i\frac{d}{dt}\begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix} = \mathcal{H}\begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix} = \left(\mathbf{M} + \mathbf{i\Gamma}\right)\begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix}$$

diagonalising the matrix to get the mass eigenstates which propagate in time:

$$K_1 = \tfrac{1}{\sqrt{2}}\left(K^0 + \bar{K}^0\right) \qquad K_2 = \tfrac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right)$$

$$\Rightarrow \quad K^0 = \tfrac{1}{\sqrt{2}}\left(K_1 + K_2\right) \qquad \bar{K}^0 = \tfrac{1}{\sqrt{2}}\left(K_1 - K_2\right)$$

with

$$K_1(t) = K_{1,0}\,\exp(im_1 t - \Gamma_1 t) \qquad K_2(t) = K_{2,0}\,\exp(im_2 t - \Gamma_2 t)$$

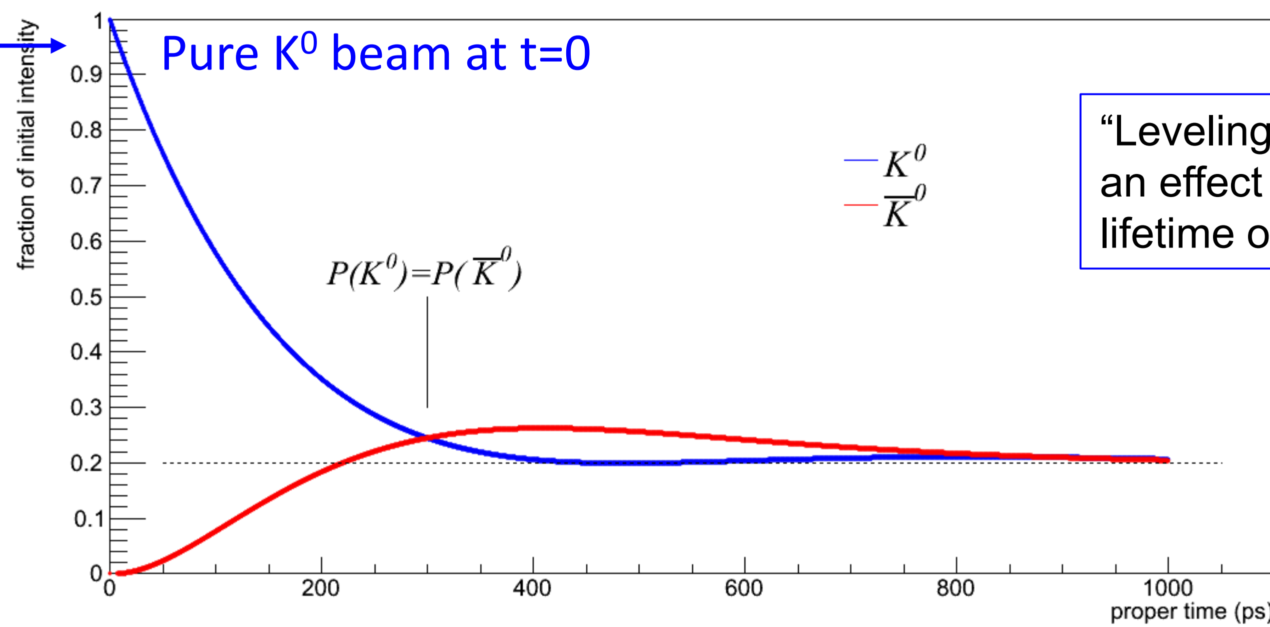
(will be discussed in detail in section 3)

$$\mathcal{P}\left(K^0(t=0)\rightarrow K^0\right)(t)=\tfrac{1}{4}\left(e^{-\Gamma_1}+e^{-\Gamma_2}+2e^{-(\Gamma_1+\Gamma_2)t/2}\cos\Delta mt\right)$$

$$\mathcal{P}\left(K^0(t=0)\rightarrow \bar{K}^0\right)(t)=\tfrac{1}{4}\left(e^{-\Gamma_1}+e^{-\Gamma_2}-2e^{-(\Gamma_1+\Gamma_2)t/2}\cos\Delta mt\right)$$

(the same for $\bar{K}^0(t=0)$)

Equal mixture of K_1 / K_2 (K_s / K_L)



"Leveling" at 25% is an effect of the long lifetime of the K_L

Only K_L :
50% K^0
50% $\bar{K}^0$

The predicted strangeness oscillation has been observed in 1957:

K^0 - $\overline{K^0}$ oscillation   (K^0 beam)

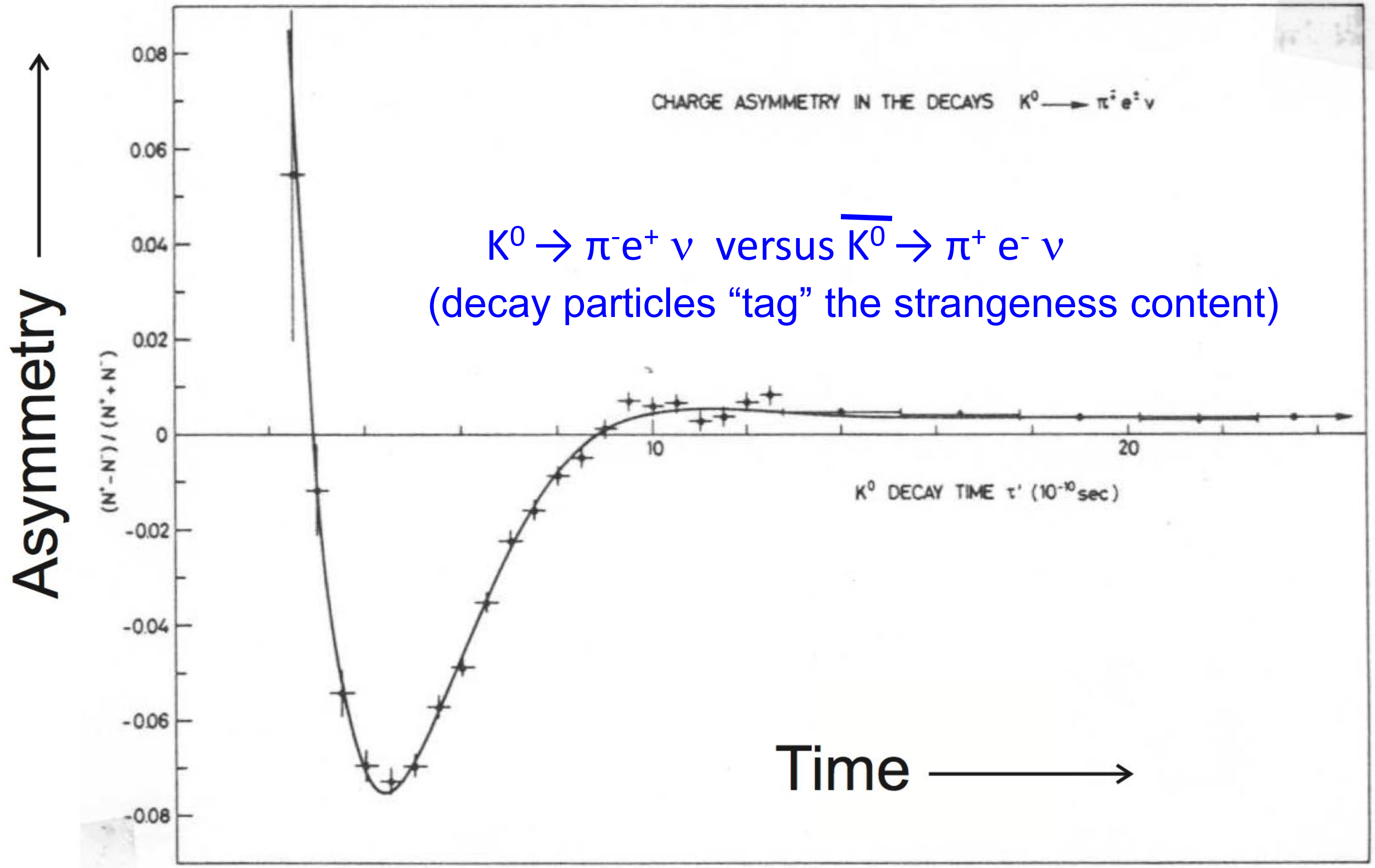


Fig. 1. The charge asymmetry as a function of the reconstructed decay time τ' for the K_{e3} decays. The experimental data are compared to the best fit as indicated by the solid line.

c) Regeneration

Strong interaction of neutral Kaons depend on strangeness S=±1.
Reason: matter is not CP symmetric.

$$\bar{K}^0 + n \to K^- + p \qquad \Leftrightarrow \qquad K^0 + p \to K^+ + n$$

$$\bar{K}^0 + p \to \Lambda^0 + \pi^+$$

“Baryon” reaction does exist with matter

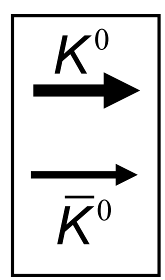
$$\bar{d}s + uud \to usd + \bar{d}u \qquad\qquad d\bar{s} + uud \to xx\bar{s} + dx$$

Cross section of $\bar{K}^0$ with matter > Cross section of K^0 with matter.

Strong interaction distinguishes the strangeness components of the propagating physical states $K_1, K_2 \left(K_S, K_L\right)$

A beam with equal fraction of K^0 and $\bar{K}^0$ (e.g. a pure K_L beam) will contain after the passage of matter slightly more K^0 (absorption of $\bar{K}^0$)

$$\underset{K_L}{K_2} = \tfrac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right) \Rightarrow$$



$$\Rightarrow \underset{K_L}{K_2} + \varepsilon \underset{K_S}{K_1}$$

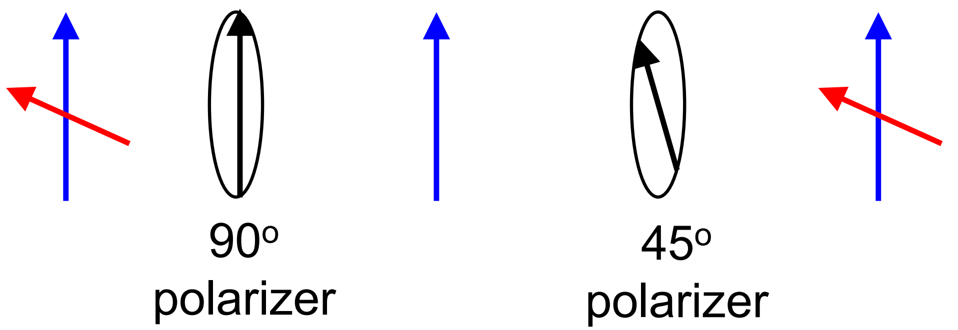
Regeneration of K_S from a pure K_L beam after passage of matter.

Regeneration was observed in 1960:

Propane bubble chamber @distance of ~100 K_s lifetimes:
$\Rightarrow$ Observation of $K_S \rightarrow \pi\pi$ if the Kaon beam passed a ~15 cm thick alu slab.

Remark:
Regeneration is a typical effect of a 2-state system $\Rightarrow$ basis change.

(Classical example: Polarization of light
vertically polarized light $\Rightarrow$ 45^o polarizer $\Rightarrow$ comp. w/ horizontal polar.)



2.2. Observation of CP violation

Already in 1963, a bubble chamber experiment studying the regeneration effect measured an anomalous excess of 2π events from a K_L beam traversing hydrogen:

"… the possibility of interpreting the events as 2π decays of the K_2 (K_L) which would be allowed if CP invariance were violated, is excluded by the result of 411 K_2 decays in cloud chambers, none of which were consistent with a 2π decays."

$$\text{CPV} \leq \tfrac{1}{411}$$

Cronin, Fitch & Turlay (1964):

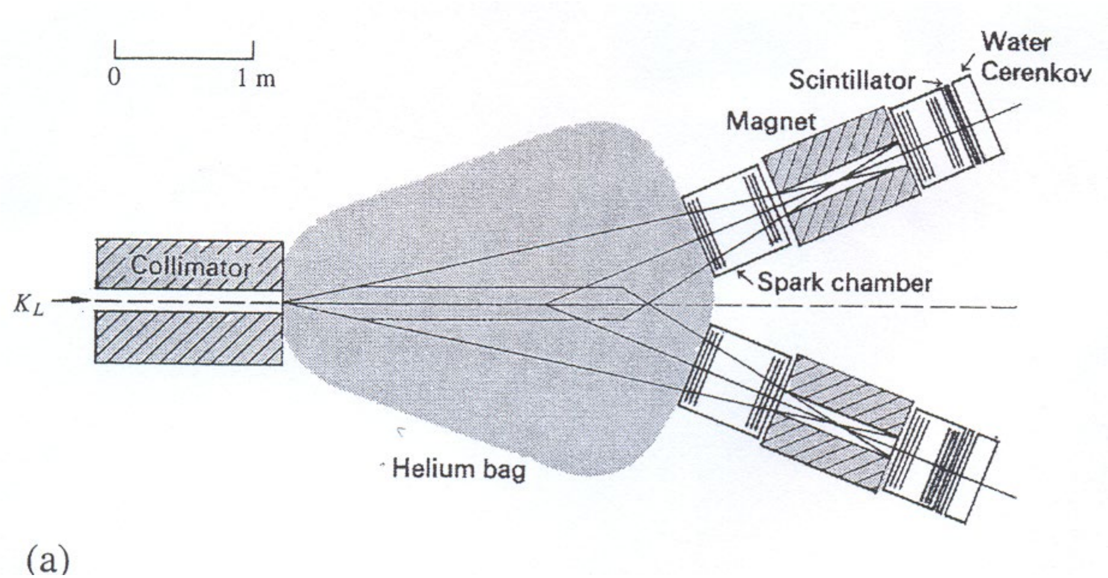
Experiment to study this anomaly and to improve the limit on $K_L \to \pi\pi$.

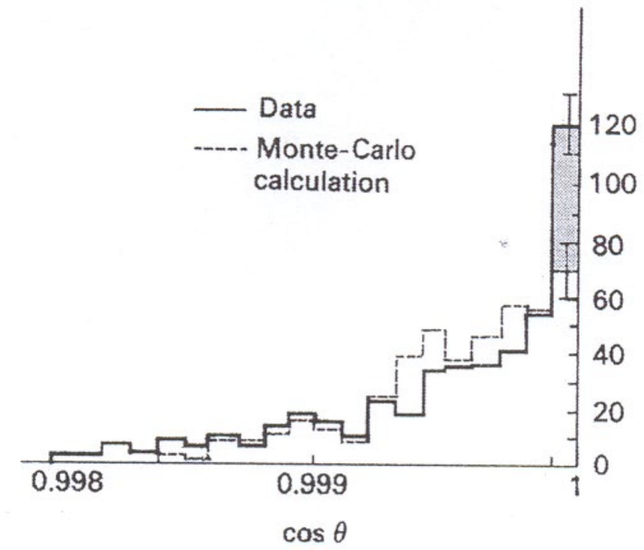
Instead they observed the decay $K_L \to \pi\pi$ (excess of 45 ± 9 events):

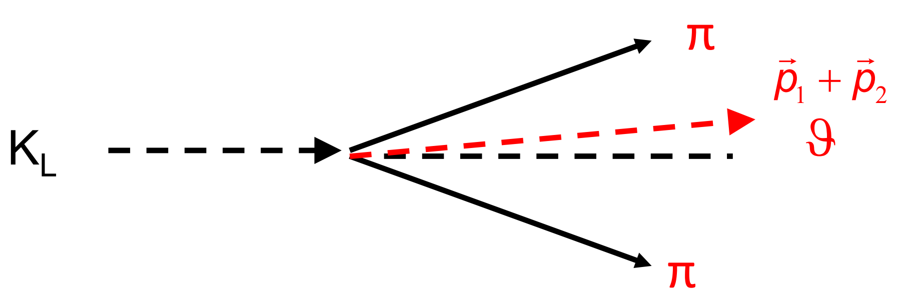
$$\frac{\Gamma\left(K_L \to \pi\pi\right)}{\Gamma\left(K_L \to \text{charged particles}\right)} = \left(2.2 \pm 0.4\right) \cdot 10^{-3}$$

Observation of CP Violation

Christenson, Cronin, Fitch, Turlay, 1964







$$K_L \to \pi^+\pi^-$$

$$CP = +1$$

$$BR \sim 2 \cdot 10^{-3}$$

Many discussion about the correctness and the interpretation of the result. The possibility of CP violation was not accepted as easily as parity violation: CP was considered an important symmetry of nature: no means to distinguish between “a particle” and “an anti-particle” world if CP was conserved.

With the observation of CPV there is a clear distinction between particle and anti-particle world possible.

A conclusive / decisive observation would be:

In presence of CP violation K_S and K_L when decaying to a CP eigenstate (e.g. $K_{S,L} \to \pi\ \pi$) can interfere!

For a K^0 $\left(\bar{K}^0\right)$ produced at t=0 and propagating freely in vacuum the decay rate to ππ is given by:

$$\Gamma\left(K^0(t=0)\to\pi\pi\right)(t) \sim e^{-\Gamma_S t} + \left|\eta_{\pi\pi}\right|^2 e^{-\Gamma_L t} \pm 2\left|\eta_{\pi\pi}\right| e^{-\left(\Gamma_S+\Gamma_L\right)t/2}\cos\left(\Delta m t - \phi_{\pi\pi}\right)$$

$$\Gamma\left(\bar{K}^0(t=0)\to\pi\pi\right)(t)$$

Interference of K_S and K_L

$$\eta_{\pi\pi} = \left|\eta_{\pi\pi}\right| e^{i\phi_{\pi\pi}} = \frac{A\left(K_L\to\pi\pi\right)}{A\left(K_S\to\pi\pi\right)}$$

The interference with ± for K^0 $\left(\bar{K}^0\right)$ is a sign for CP violation.

Because of $e^{-t/(2\tau_S)}\left|\eta_{\pi\pi}\right|$ interference effects are large only for t ≈ $O(\tau_S)$
→ in the 1960s it was difficult to perform the experiment that close to the production target.

However one can establish the same kind of interference also after a regenerator with an initially pure K_L beam (far away from the target).

Initially pure K_L beam develops a coherent K_S component after a regenerator:

$$\psi_K \sim |K_L\rangle + \rho \cdot |K_S\rangle$$

With the complex quantity $\rho = |\rho| e^{i\phi_\rho}$

describing coherent regeneration
(ratio of the two K amplitudes)

$\Rightarrow$ $\pi\pi$ yield after regenerator (3 components):

$$\Gamma\left(K^0(t=0) \to \pi\pi\right)(t) \sim |\rho|^2 e^{-\Gamma_S t} + |\eta_{\pi\pi}|^2 e^{-\Gamma_L t}$$

$$\bar{K}^0$$

$$\pm 2|\eta_{\pi\pi}||\rho| e^{-\left(\Gamma_S+\Gamma_L\right)t/2} \cos\left(\Delta m t - \left(\phi_{\pi\pi} - \phi_\rho\right)\right)$$

K_S – K_L interference large if ρ and $\eta_{\pi\pi}$ have similar magnitude.

<u>Fitch et al. 1965:</u>
Using a K_L beam and a "diffuse Be" regenerator (Be smeared over ~1m $\cong 7\tau_S$)
the K_S and K_L intensities are quasi constant:

K_S and CP violating $K_L \to \pi\pi$ interfered: $\pi\pi$ yield was not the sum of K_L decays and regenerated K_S but rather up to 2times that value (interference).

CP violation was established!

Interference of K_S and K_L after regeneration was used to measure mass difference Δm and the difference between the CP phase $\phi_{\pi\pi}$ and the regeneration phase (Alff-Steinberger et al., 1966).

A similar experiment to the Fitch et al. measurement was repeated at CERN (Geweniger et al. 1974) as the first application of the newly invented multi-proportional wire chamber $\rightarrow$ much higher rates than spark chamber.

CP Violation: Interference-effect

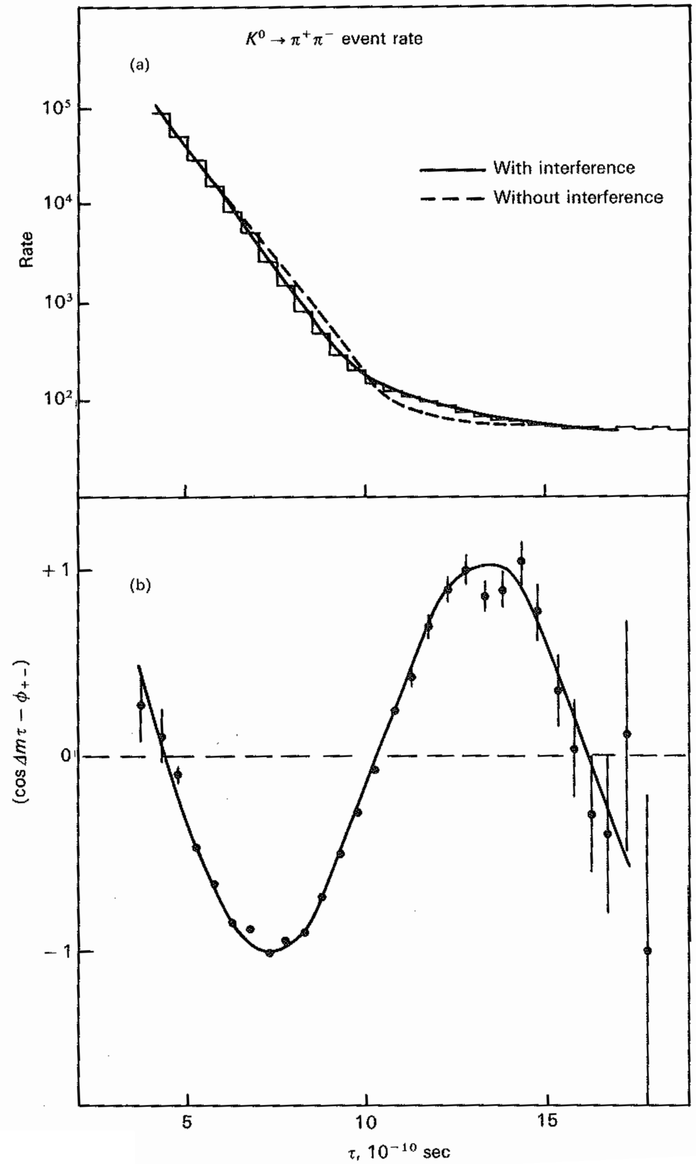


Figure 7.26 (a) Event rate for $\pi^+\pi^-$ decays from a neutral-kaon beam as a function of proper time, demonstrating that the best fit needs the existence of interference between K_L- and K_S-amplitudes. (b) The interference term extracted from the results in (a). From the fit one can obtain the $K_L - K_S$ mass difference Δm and the phase angle ϕ_{+-} between the two amplitudes. (After Geweniger *et al.* 1974.)

$K_L \to \pi\pi$ and $K_S \to \pi\pi$ can interfere:

We see not only the effect of regenerated $K_s \to \pi\pi$ but also effect of interference term which oscillates in time.

Neutral Kaon beams:

A NEW DETERMINATION OF THE $K^0 \to \pi^+\pi^-$ DECAY PARAMETERS

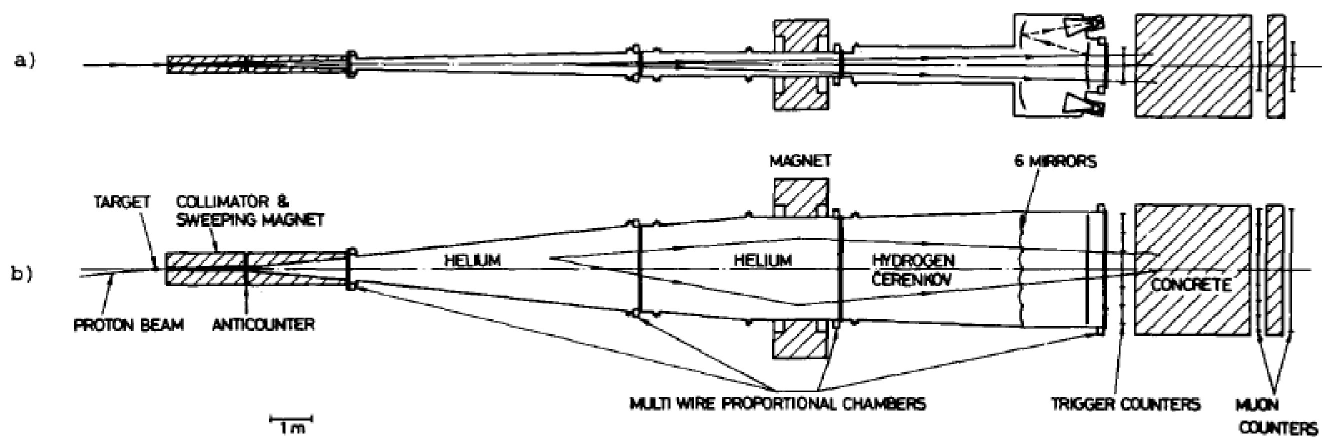


Fig. 1. Experimental lay-out. a) side view, b) top view

The experiment was performed in a short neutral beam at the CERN Proton Synchrotron, providing neutral kaons over the momentum range 3–15 GeV/c. The main elements of the set-up [2] are shown in fig. 1. The neutral hadrons are produced by an external proton beam of 24 GeV/c hitting a 4.5 cm long platinum target, 4×4 mm^2 in cross-section. The secondaries are selected at an average angle of 75 mrad by a tapered uranium collimator, 2 m long, imbedded in a magnetic field of 20 kG. It is followed by a 9 m long decay volume filled with helium. The vector

The theoretically expected distribution in proper time is:

$$I_{2\pi}(\tau) = [S(p) + \bar{S}(p)]\,\{\exp(-\Gamma_S \tau)$$

$$+\, 2A(p)|\eta_{+-}|\exp[-(\Gamma_L + \Gamma_S)\tau/2]\cos(\Delta m \tau - \phi_{+-})$$

$$+\, |\eta_{+-}|^2 \exp(-\Gamma_L \tau)\},$$

where $S(p)$ and $\bar{S}(p)$ are the production intensities of K^0 and $\bar{K}^0$ and $A(p)$ measures the initial admixture of K^0 and $\bar{K}^0$:

$$A(p) = \frac{S(p) - \bar{S}(p)}{S(p) + \bar{S}(p)}.$$

This expression is fitted to the data in 0.5 GeV/c momentum bins to find Γ_S, $|\eta_{+-}|$, ϕ_{+-} and unparametrized $S(p)$ and $\bar{S}(p)$ assuming Δm and Γ_L to be known. The experimentally-determined phase ϕ_{+-} is a linear function of Δm.

Geweniger et al. Phys Lett. B 48 (1974) 483.
Geweniger et al. Phys Lett. B 48 (1974) 488.