3.2 Observation of CP violation

Historical Remark:

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 „decay of the K_2 (K_L) which would be allowed if CP invariance were violated is excluded ..... by other experiments..."

Cronin, Fitch & Turlay 1964 → Figure

→ Experiment to study this problem and to improve the limit on $K_L \to \pi\pi$ decays.

Instead they observed the $K_L \to \pi\pi$ decay:

↓ Access of 45 ± 9 events } →

$$\frac{\Gamma(K_L \to \pi\pi)}{\Gamma(K_L \to \text{charged particles})} = (2.0 \pm 0.4)\, 10^{-3}$$

→ Many discussions about the correctness of the measurement and also about the interpretation (the possibility of CP violation was not accepted as easily as parity violation: much more fundamental consequences!!)

Decisive/conclusive measurement

In presence of CPV K_S and K_L interfere when decaying to CP eigenstates

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

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

$\bar{K}^0$

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

interference term

with $\eta_{\pi\pi} = |\eta_{\pi\pi}| \cdot e^{i\phi_{\pi\pi}} = \dfrac{A(K_L \to \pi\pi)}{A(K_S \to \pi\pi)}$

The same kind interference is also detected after the K_S regeneration of a K_L beam:

$$\Psi(t=0) \sim |K_L(t=0)\rangle + \rho\, |K_S(t=0)\rangle$$

exit of regenerator

where $\rho = |\rho| e^{i\phi_\rho}$ describes the „coherent" regeneration.

<u>$\pi\pi$ - component from the K^0 ($\bar{K}^0$) beam:</u>

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

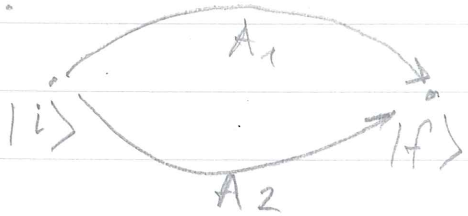
$$\pm 2|\eta_{\pi\pi}||\rho| \cos(\phi_{\pi\pi} - \phi_\rho)$$

An experiment performed (Fitch et al. 1965) indeed showed that there is an interference term present:
Proved that the $K_S \to \pi\pi$ and $K_L \to \pi\pi$ were the same
→ CP was violated in the decay $K_L \to \pi\pi$!

3.3 CP violation in meson decays – general remarks

CP violation is linked to the CKM phases in the transition amplitudes. But: all observable quantities are in general „squares" of matrix-elements
→ phases do not lead easily to measurable effects
(absolute phases are not observable)

Phase differences are observable via interference effects:
At least two interfering amplitudes are required to observe a phase related effect and to study CP violation:



$$\mathcal{A}(i \to f) = |A_1| e^{i\phi_1} + |A_2| e^{i\phi_2}$$

↓

$$(*) \quad |\mathcal{A}(i \to f)|^2 = |A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos(\phi_1 - \phi_2)$$

However this is also not sufficient to observe CPV:
CP conjugation is changing the sign of both weak phases ϕ_1 and ϕ_2 such that one obtains for the CP conjugated version of $(*)$:

$$|\mathcal{A}(\bar{i} \to \bar{f})|^2 = |A_1|^2 + |A_2|^2 + 2 |A_1||A_2| \cos(\phi_1 - \phi_2)$$

(exactly the same expression!)

In order to observe CP violation additional „strong" phases δ_1 and δ_2 which do not change sign, must be present:

$$A(i \to f) = |A_1| e^{i\phi_1} e^{i\delta_1} + |A_2| e^{i\phi_2} e^{i\delta_2}$$

$$A(\bar{i} \to \bar{f}) = |A_1| e^{-i\phi_1} e^{i\delta_1} + |A_2| e^{-i\phi_2} e^{i\delta_2}$$

For the diff. of the transition rate one now finds:

$$|A(\bar{i} \to \bar{f})|^2 - |A(i \to f)|^2 = 2|A_1||A_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

<u>Problem:</u> The strong phases are a result of the interaction between the hadronic final state particles → difficult to calculate

→ The observation of CP violation in many cases does not allow to conclude on the weak phases!
(only special cases lead to information on the weak phases)

Before coming back and explaining the origin of the observed CPV in kaon decays I like to introduce the phenomenologie of neutral meson mixing.

K^0 - $\overline{K^0}$ oscillation

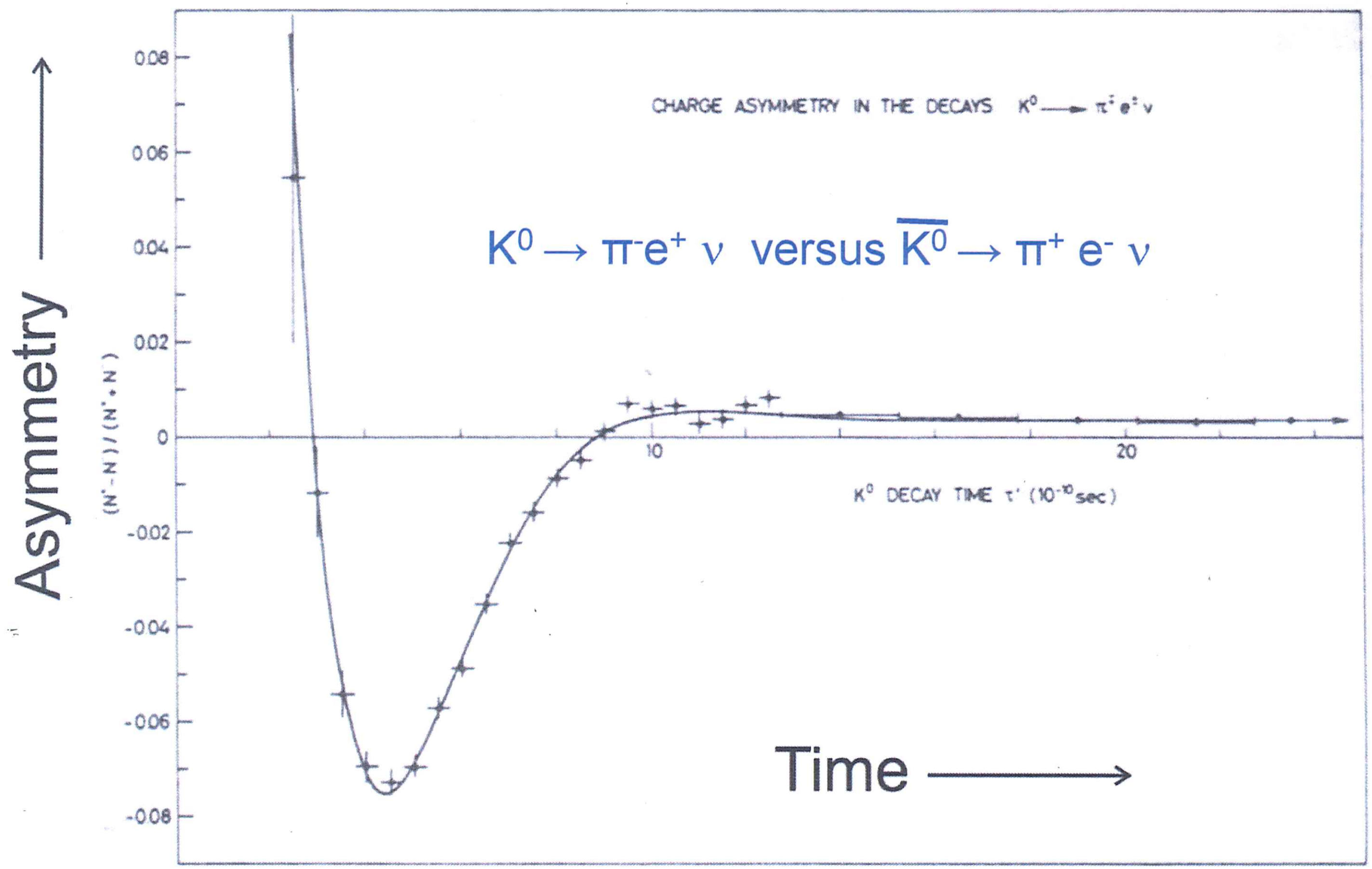
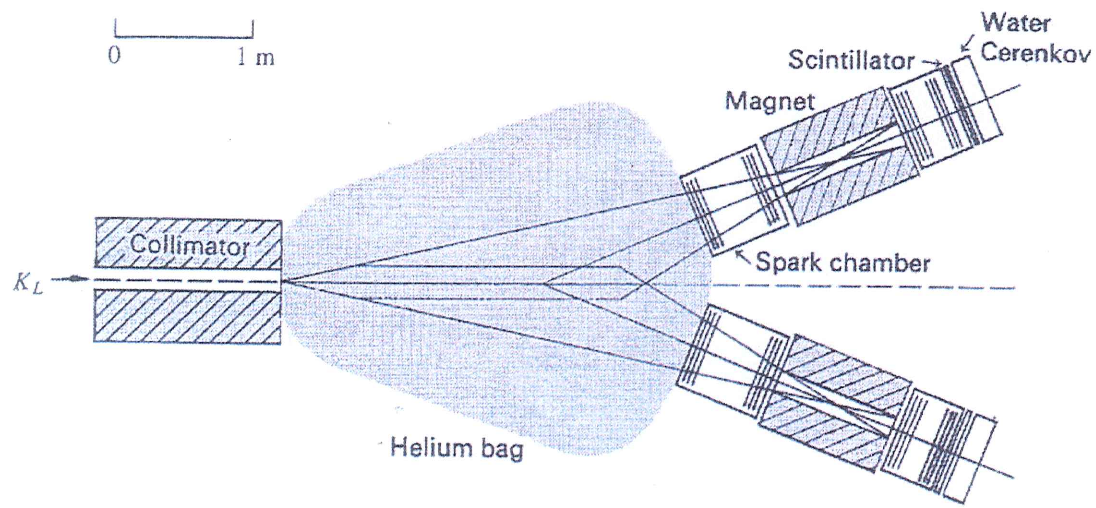


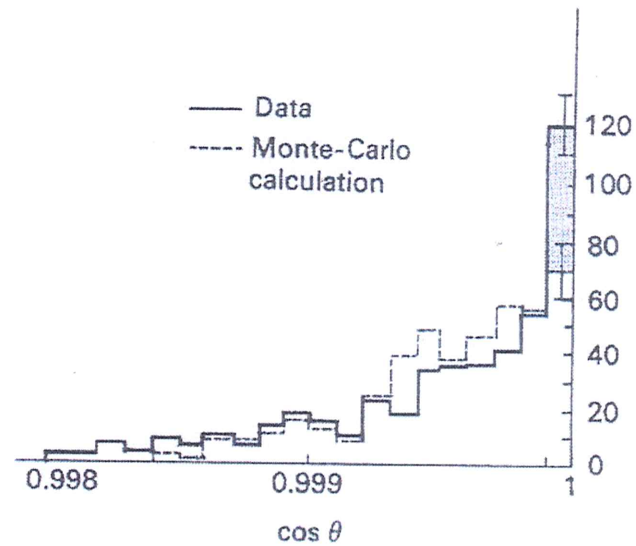
Fig. 1. The charge asymmetry as a function of the reconstructed decay time τ' for the K_{e3} decays. The experimental data are compared to the best fit as indicated by the solid line.

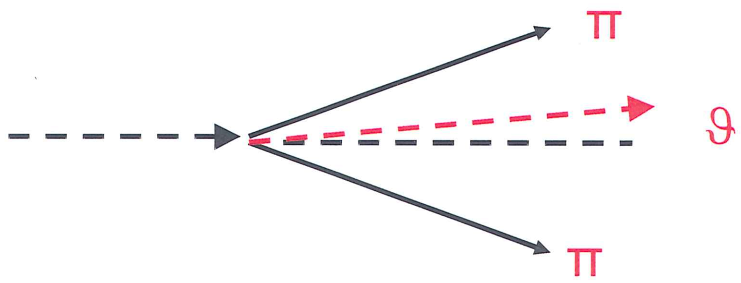
Observation of CP Violation

Christenson, Cronin, Fitch, Turlay, 1964



(a)



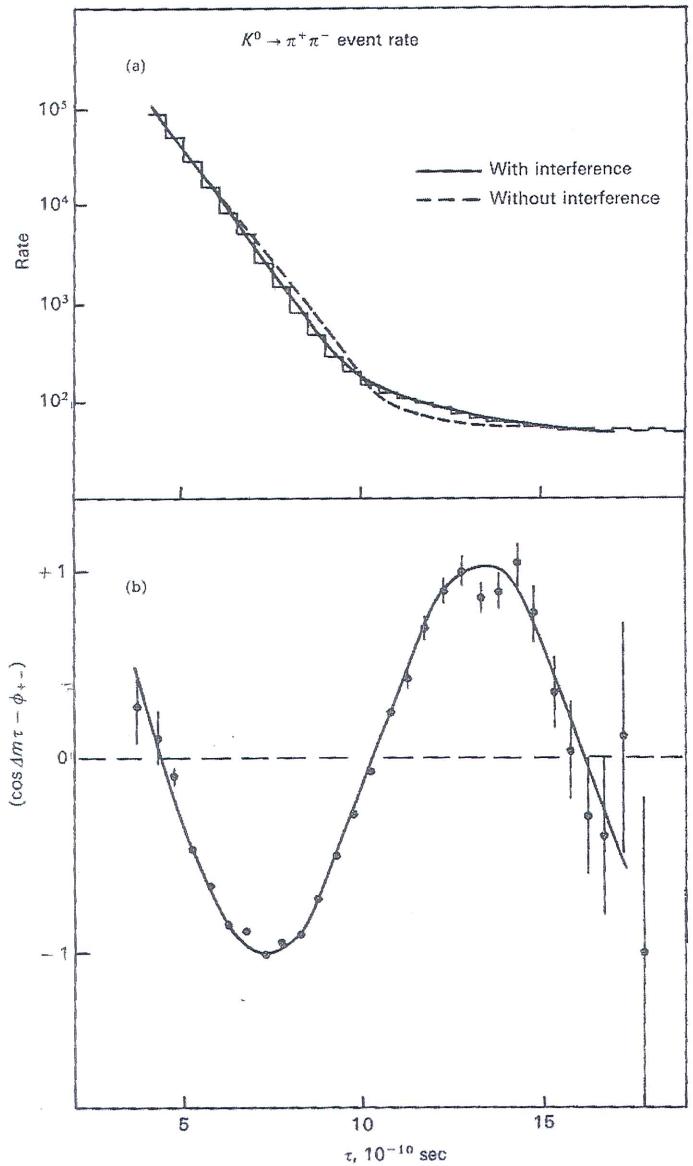


$K_L \to \pi^+\pi^-$

$CP = +1$

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

CP Violation: Interference-effect



$K_L \to \pi\pi$ 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.

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.)

Neutral Mesons: physical states