3. Strange Mesons (Kaon-Physics)

$K^+ (u\bar{s})$ $K^- (\bar{u} s)$ $m_K = 494\,MeV$ $\tau_K = 12.4\,ns$

$K^0 (d\bar{s})$ $\bar{K}^0 (\bar{d} s)$ $m_{K^0} = 498\,MeV$

K^0_S, K^0_L $\tau_{K_S} = 90\,ps$ $\tau_{K_L} \approx 52\,ns$

History of is rich in ground-breaking discoveries:

- new quantum number (strangeness) → Quark model & SU(3)
- mixing and regeneration
- CP violation, CP-Violation

3.1 Discovery of „strange" particles

1947 Rochester & Butler:

Discovery of a V_0 (K^0_S) particle in a cosmic ray shower provoked by a lead target in a cloud chamber: longlived neutral particle decaying into 2 tracks with „very striking character" (V shape) → see Fig.

A large number of subsequent cosmic ray experiments led to the discovery of further „unstable particles" with typ. life-times of $10^{-9} \ldots 10^{-10}\,s$.

Eg.: R Brown et al. 1949 τ^+ $(K^+) \to \pi^+\pi^-\pi^+$

Not clear which of the new particles are the same but decaying differently and which are different. Historical:

Old	Today
τ^+	$K^+ \to \pi^+\pi^-\pi^+$
V_1^0	$\Lambda^0 \to p\pi^-$
Θ^0	$K^0_S \to \pi^+\pi^-$
Θ^+	$K^+ \to \pi^+\pi^0$

Famous example: θ/τ - Puzzle

2 particles τ^+ and θ^+ with same mass but differ. parity:

$$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \qquad CP = -1$$
$$\theta^+ \rightarrow \pi^+ \pi^0 \qquad P = +1$$

T.D. Lee & Yang proposed that particles are the same, but parity is not conserved → discovery of $\not{P}$ by Wu.

With the first proton synchrotrons:

- Cosmotron at BNL (1951) → 3.3 GeV
- Bevatron at BNL (1954) → 6.2 GeV

it was possible to produce „strange" particles copiously in association with each other in strong IA:

$$\text{eg:} \quad \pi^+ + p \longrightarrow \underset{S=+1}{K^+} + \underset{-1}{\bar{K}^0} + p \qquad E_\pi > 1.5 \text{ GeV}$$

(→ allows to produce pure K^0 beams!)

From the observed large production cross sections it was concluded that the lifetimes should be only $\approx \mathcal{O}(10^{-20})$ if the new particles were decaying strongly.

↳ Introduction of new additive quantum number = strangeness which is conserved in strong IA but which is violated in weak decays: $K^0 (u\bar{s}) \quad S = +1$

The new quantum number together with strong isospin opened the way to flavor SU(3) classification of hadrons and to the introduction of the quark model (u, d, s) as the fundamental representation by Gell-Mann.

Ditto the additive quantum number, anti-particles must have opposite strangeness to that of particles:
↳ 2 neutral K with $S = \pm 1$

In a seminar given by Gell-Mann in Chicago Fermi asked how the 2 neutral kaons decaying into the same final states could retain their individuality.

Considerations by Gell-Mann & Pais:

Neutral particles: { either self-conjugate: π^0, γ ; particle/anti-p with distinct QN }

As long as the strong IA is considered K^0 belongs to the 2nd type: $K^0 (S=+1) \xrightarrow{C} \bar{K}^0 (S=-1)$

However since weak IA does not conserve strangeness K^0 and $\bar{K}^0$ can decay to the same indistinguishable final state and therefore couple through the decay process:

$$K^0 \to \pi\pi \to \bar{K}^0$$

→ transitions $K^0 \leftrightarrow \bar{K}^0$ possible through decays!

Non self-conjugated strong states K^0:

$CP|K^0\rangle = |\bar{K}^0\rangle \qquad CP|\bar{K}^0\rangle = K^0$ } mix
(w/ appropriate choice of the phases)

If CP is valid symmetry it can be used to characterise the physical mixed states

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

w/ $CP|K_1\rangle = +K_1 \qquad CP|K_2\rangle = -K_2$

Predictions by Gell-Mann & Pais:

1) Existence of 2 neutral self-conjugated physical states; K_1, K_2 which are (if CP conserved) CP eigenstates and which have different lifetimes and masses!

↳ Discovery of K_L^0 (K_2) at the cosmotron in 1956
. Long lived $K_L^0 \to \pi\pi\pi$ $\quad \tau_{K_2} = 5.17 \cdot 10^{-8}s$
$\tau_{K_S} = 0.89 \cdot 10^{-9}s$

(huge lifetime difference is result of different phase space for the 3-body K_L and 2 body K_S decays)

2) Oszillation / mixing of K^0 and $\bar{K}^0$:
Since $K^0, \bar{K}^0$ strangeness states could mix via $K^0 \to \pi\pi \to \bar{K}^0$ they should not exhibit a pure exponential lifetime behavior but an oscillatory behaviour:
When propagating through the vacuum the two strangeness states are ~~th~~ not 2 distinguishable particles but the 2 ~~states~~ components of a 2 state system:

$$\begin{cases} P(K^0(t=0) \to K^0)(t) = \frac{1}{4}\left(e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2\, e^{-(\Gamma_S+\Gamma_L)/2 \cdot t} \cos(\Delta m t)\right) \\ P(\bar{K}^0(t) \to \bar{K}^0)(t) = \frac{1}{4}\left(\qquad - 2\, e^{-(\Gamma_S+\Gamma_L)/2 \cdot t} \cos(\Delta m t)\right) \end{cases}$$

→ see Figs.
Strangeness oszillation has been observed in 1957

3) Regeneration

Strong interaction with matter depends on strangeness (matter is not C-symmetric):

$$\bar{K}^0 + n \rightarrow K^- + p$$
$$\bar{K}^0 + p \rightarrow \Lambda + \pi^+$$
} both reactions possible

$$K^0 + p \rightarrow K^+ + n$$

↳ cross section of $\bar{K}^0$ w/ matter > cross section of K^0 w/ matter

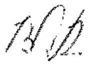
↳ Strong IA distinguishes the two strangeness components of the propagating physical state:

A beam with equal fraction of K^0 $\bar{K}^0$ (e.g. a pure K_2 beam) will contain after the passage of matter slightly more K^0

$$K_2 = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \xrightarrow{\text{Matter}} K_L + \epsilon K_S$$

"regeneration of K_S"

Regeneration was observed in 1960:
Propane bubble chamber @ distance of ~ 100 τ_S:
Observation of $K_S \rightarrow \pi\pi$ if kaon beam passes ~1 cm thick alu absorber.



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:

↓

A cause 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:

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

$$\bar{K}^0 \qquad \pm 2 |\eta_{\pi\pi}| e^{-(\Gamma_S + \Gamma_L)/2 \cdot t} \cos(\Delta m t - \phi_{\pi\pi})$$

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 [illegible] 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.

$\pi\pi$ – component from the K^0 ($\bar{K}^0$) beam:

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

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

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 $K_L \to \pi\pi$!