3. Strange Mesons (Kaon-Physics)

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

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

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

$I(J^P) = \frac{1}{2} (0^-)$

History of kaon physics is remarkably rich in ground-breaking discoveries:

- discovery of new quantum number (strangeness) → quark model
- mixing & regeneration
- P violation (θ/τ puzzle), CP violation

3.1 Discovery of „strange' particles

1947, Rochester & Butler: Discovery of a V_0 (K^0_S) in cosmic rays
Cosmic ray shower provoked by a lead target in a cloud chamber led to the observation of longlived neutral particle, decaying into 2 „further tracks of very striking character" (V shape).

→ see Fig.

Alredy in 1943 there were indications for a particle of a mass of ~ 980 m_e (Leprince-Ringuet & L'Heritiere using a Wilson chamber) which would mean that the K^0 was seen before the pion (discovered in 1947)

Wilson chamber or Cloud chamber / Nebelkammer.

A large number of different cosmic ray experiments led to the discovery more unstable particles with typ. lifetimes of $10^{-8} \dots 10^{-10}$ s.

E.g. R. Brown et al. 1949 $\tau^+(K^+) \rightarrow \pi^+\pi^-\pi^+$

It was not clear which of the new particles are the same (but a different decay) and which of them were different. Historically the naming was as follows:

Old	Today	
τ^+	$K^+ \longrightarrow \pi^+\pi^-\pi^+$	
V_1^0	$\Lambda^0 \longrightarrow p\pi^-$	
$V_2^0(\theta^0)$	$K_S^0 \longrightarrow \pi^+\pi^-$	
~~κ~~	$K^+ \rightarrow \mu\nu$	$K_{\mu 2}$
	$\rightarrow \mu\pi^0\nu$	$K_{\mu 3}$
$\chi(\theta^+)$	$K^+ \rightarrow \pi^+\pi^0$	
V^+, Λ^+	$\Sigma^+ \rightarrow p\pi^0, n\pi^+$	

Example: θ/τ Puzzle

$\tau^+ \rightarrow \pi^+\pi^-\pi^-$ CP = −1

Dalitz et al. 1956

$\theta^+ \rightarrow \pi^+\pi^0$ CP = +1

Mass and spin of the θ/τ the same

→ T.D. Lee & Yang: Maybe θ and τ same particle (K^+) but Parity is violated

With the advent of the first proton synchrotrons:

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

"Strange" particles were also produced copiously "in association with each other also in the strong interaction:

(1) $p + \pi \longrightarrow \Lambda + K^0$ K⁰ is associated with hyperon.

$E_\pi > 0.91$ GeV $\quad S \quad -1 \quad +1$

A $\bar{K}^0$ is produced in association with $K/\bar{\Lambda}$:

(2) $\pi^+ + p \longrightarrow K^+ + \bar{K}^0 + p$

$E_\pi > 1.5$ GeV $\quad S \quad +1 \quad -1$

(3) or $\pi^- + p \longrightarrow \underline{\bar{\Lambda}} + \bar{K}^0 + n + n$

$E_\pi > 6.0$ GeV $\quad +1 \quad -1$

Threshold energy of the pion:

(1) $E_\pi > 0.91$ GeV
(2) $E_\pi > 1{,}50$ GeV
(3) $E_\pi > 6.0$ GeV

→ allows to produce a pure K^0 beam!

From large production cross sections one could conclude that the lifetime of strange particles would be about $\times 10^{10}$ smaller if their decay would be mediated by strong IA

→ Introduction of a new quantum number

by Gell-Mann & Pais
(additive) (multiplicative)

The new unstable particle possess a new additive quantum number „strangeness" which is conserved in strong interaction but is violated in weak decays.

$K^0(u\bar{s})$ $S = +1$
$K^+(u\bar{s})$ $S = +1$
$\Lambda\,(uds)$ $S = -1$
$\Sigma^{+,0}$ $S = -1$

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

With the additive quantum number scheme anti-particles are required to have opposite strangeness to that of particles!

→ 2 neutral K particles with $S = \pm 1$!

In a seminar given by Gell-Mann in Chicago Fermi asked how the 2 neutral kaons which would decay into the same final states could retain any individuality?

→ Interesting considerations by Gell-Mann & Pais (1955):

Neutral particle 2 possibilities $\begin{cases} \text{self-CP conjugate: } \gamma, \pi^0 \\ \text{particle + a-particle with distinct quantum numbers.} \end{cases}$

As long as strong interaction is considered K^0 belongs to the 2nd type (strangeness conservation).

$$K^0 \quad S=+1 \longrightarrow \bar{K}^0 \quad S=-1$$

However the weak interaction is not conserving strangeness
→ K^0 and $\bar{K}^0$ decay to the same indistinguishable final state and therefore couple through the process

$$K^0 \longrightarrow \pi^+\pi^- \longrightarrow \bar{K}^0$$

→ Transitions $K^0 \Leftrightarrow \bar{K}^0$ would be allowed through the common (virtual) decays!
(CPT symmetry enforcing $\underbrace{m_{K^0} = m_{\bar{K}^0}}_{\text{mass degeneration}}$ could enhance these transitions)

Non-self-conjugated K^0:

$$CP|K^0\rangle = |\bar{K}^0\rangle \qquad CP|\bar{K}^0\rangle = |K^0\rangle$$

with appropriate choice of phases

If CP is a valid symmetry it can be used to characterize the physical states:

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

with $CP|K_1\rangle = +|K_1\rangle \quad CP|K_2\rangle = -K_2$

Observable: Mass diff between K_1 K_2 : $\Delta m = m_2 - m_1 = m_L - m_S = 3.5 \cdot 10^{-6}$ eV

→ ① Prediction of two neutral self-conjugated physical states, linear combinations of the flavor states.

If CP is conserved, K_1 and K_2 decay differently

$K_1 \to$ CP even states
$K_2 \to$ CP odd states

Consequence: - different lifetimes of K_1 and K_2
- masses could also be different!
(virtual $K^0 \leftrightarrow \bar{K}^0$ transitions for $K_{1,2}$ involve different states!)

K_1 and K_2 are not constrained by CPT symmetry!

→ Discovery of K_L at the cosmotron: (Lande et al, 1956)

Long lived $K_L \to \pi\pi\pi$
($K_S \to \pi\pi$ was already known)

$\underset{\sim}{K_S}$: $\tau_S = 0{,}89 \cdot 10^{-10}$ s $K_S \to \pi\pi$
K_1

$\underset{\sim}{K_L}$: $\tau_L = 5{,}17 \cdot 10^{-8}$ s $K_L \to \pi\pi\pi$
K_2

Huge lifetime difference is a result of the phase space
If CP is conserved: $K_L \to 3\pi$ (CP odd) $K_S \to 2\pi$ (CP even)

Predictions by Gellmann & Pais

- ① Prediction of 2 neutral self-conjugate kaon states with diff mass/lifetime.
- Flavor states $K^0, \bar{K}^0$ mix and cannot be the physical states:

- If CP is conserved, CP symmetry can be used to characterize the physical states:

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

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

Masses can be different: $\Delta m = m_2 - m_1 \approx 3.5\, 10^{-6}$ eV

- if CP is conserved K_1 and K_2 must decay different
  $K_1 \to$ CP even states
  $K_2 \to$ CP odd states
  → Lifetime of K_1 and K_2 are different.

Remark: K_1, K_2 are not constrained by CPT!

Discovery of longlived K_2 at cosmotron

$K_2 \to 3\pi$ with $\tau(K_2) \gg \tau(K_1)$

→ use lifetime to distinguish the physical states.

$K_1 = K_S$ $\tau_S = 0.89 \cdot 10^{-10}$ s $K_S \to \pi\pi$

$K_2 = K_L$ $\tau_L = 5.17 \cdot 10^{-8}$ s $K_L \to \pi\pi\pi$

The lifetime difference is a result of the phase space difference of the CP odd ($\to 3\pi$) and CP even ($\to 2\pi$) decays

② Prediction of Gell-Mann Pais Theorie: Oszillation

Since $K^0, \bar{K}^0$ strangeness states are coupled via weak IA ($K^0 \leftrightarrow \pi\pi \leftrightarrow \bar{K}^0$) they should not exhibit a pure exponential lifetime behavior but in addition „strangeness oszillation".

→ The two strangeness states are not 2 distinguishable particle states but the components of a 2-State System which can transform into each other:

$$P(K^0(t=0) \to K^0)(t) = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S+\Gamma_L)/2\cdot t}\cdot\cos(\Delta m t)\right]$$

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

→ see Figure.

Strangeness oszillation have been observed in 1957 (Lande et al.)

From a pure K^0-beam ($S=+1$) from $p+n \to p\Lambda K^0$ one has found a Σ^- ($S=-1$) in the decay chain indicating that the K^0 has transformed into $\bar{K}^0$:

$$\bar{K}^0 + He \to \Sigma^- p p n \pi^+$$

Later the semi-leptonic decay: $K^0 \to \pi^- e^+ \nu_e$
$\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e$
was used to resolve the oszillation.

→ see. Fig 6.1 in Sozzi
(also in Trupvecus)

③ Prediction of Gell-Mann Pais Theory: Regeneration

Strong interaction of Kaons with matter depends on the Strangeness (Matter is not C-symmetric):

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

$K^0 + p \rightarrow K^+ + n$ } Reaction of anti-hyperon production not possible!

→ Cross section of $\bar{K}^0$ with matter > cross section of K^0 w/ matter

↳ Strong interaction distinguishes the two strangeness components of a physical state: A beam with equal fraction of K^0 and $\bar{K}^0$ (e.g. K_L) will contain after the passage of matter slightly more K^0.

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

K_2

"regeneration of K_S"

Experimental observation (Müller et al., 1960)

Propane bubble chamber @ distance of $\sim 100\,\tau_S$: Observation of $K_S \to \pi\pi$ if Kaon beam passes ~ 15 cm thick Absorber (Metal plate).

Remark: Even though the observed K_S, K_L states are combination of K^0 and $\bar{K}^0$, the latter do not loose their properties
→ well distinguishable in matter.
Only the free Hamiltonian (vacuum) makes no diff. between K^0, $\bar{K}^0$