

3. Strange Mesons (Kaon Physics)

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

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

$$K_S^0 \quad \tau_{K_S} = 90 \text{ ps} \quad K_L^0 \quad \tau_{K_L} = 52 \text{ ns}$$

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

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

- discovery of new quantum number (strangeness) \rightarrow quark model
- mixing & regeneration
- CP violation (θ/E Purohit), CP violation

3.1 Discovery of 'strange' particles

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

\rightarrow See Fig.

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

Wilson chamber or cloud chamber / Meitner.

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. $\Sigma^+(K^+) \rightarrow \pi^+ \pi^- \pi^+$
1949

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
Σ^+	$K^+ \rightarrow \pi^+ \pi^- \pi^+$
V_1^0	$K^0 \rightarrow p \pi^-$
$V_2^0 (\theta^0)$	$K_S^0 \rightarrow \pi^+ \pi^-$
K	$K^+ \rightarrow \mu \nu$ $K_{\mu 2}$ $\rightarrow \mu \pi^0 \nu$ $K_{\mu 3}$
$\gamma (\theta^+)$	$K^+ \rightarrow \pi^+ \pi^0$
V^+, Λ^+	$\Sigma^+ \rightarrow p \pi^0, n \pi^+$

Example: θ/τ Puzzle

Jalitz et al. $\Sigma^+ \rightarrow \pi^+ \pi^- \pi^+$ $CP = -1$
1956 $\theta^+ \rightarrow \pi^+ \pi^0$ $CP = +1$

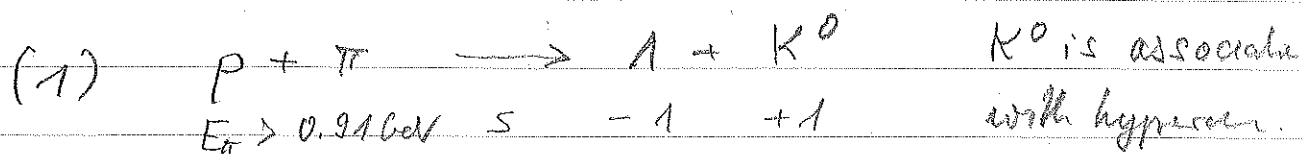
Mass and spin of the θ/τ the same

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

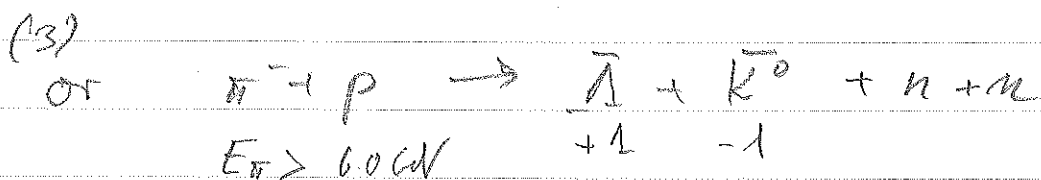
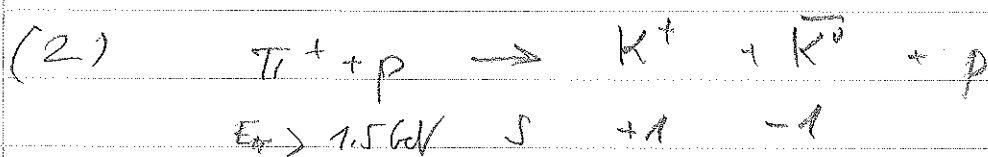
With the advent of the first proton synchrotrons:

- Cosmotron at BNL (1951); $\rightarrow 3.3 \text{ GeV}$
- Bevatron at LBNL (1954); $\rightarrow 6.2 \text{ GeV}$

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



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



Threshold energy of the pion:

$$(1) \quad E_{\pi} > 0.91 \text{ GeV}$$

$$(2) \quad E_{\pi} > 1.50 \text{ GeV}$$

$$(3) \quad E_{\pi} > 6.0 \text{ GeV}$$

\rightarrow 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 Λ

→ 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 decay.

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

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 $\left\{ \begin{array}{l} \text{self-CP conjugate: } \eta, \pi^0 \\ \text{particle + a-particle with} \\ \text{distinct quantum numbers.} \end{array} \right.$

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

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

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

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

→ Transition $K^0 \leftrightarrow \bar{K}^0$ would be allowed through the common (virtual) decays!

(CPT symmetry enforcing $m_{K^0} = m_{\bar{K}^0}$ could enhance these transitions)
 \swarrow mass degeneracy

Non-self-conjugated K^0 :

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

with appropriate choice of phases

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

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

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

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

→ 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

$K_1 \rightarrow$ CP even states

$K_2 \rightarrow$ CP odd states

Consequences: - different lifetimes of K_1 and K_2
 - masses could also be different!
 (without $K^0 \leftrightarrow \bar{K}^0$ 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 $K_L \rightarrow \pi\pi\pi$

($K_S \rightarrow \pi\pi$ was already known)

$\underbrace{K_S}_{K_1}$: $\tau_S = 0.89 \cdot 10^{-10}$ s $K_S \rightarrow \pi\pi$

K_1

$\underbrace{K_L}_{K_2}$: $\tau_L = 5.17 \cdot 10^{-8}$ s $K_L \rightarrow \pi\pi\pi$

K_2

The lifetime difference is a result of the phase space.

If CP is conserved: $K_L \rightarrow 3\pi$ (odd) $K_S \rightarrow 2\pi$ (CP even)

Predictions by Bellman & Paris

- 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:

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

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

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

- if CP is conserved K_1 and K_2 must decay different

$K_1 \rightarrow$ CP even states

$K_2 \rightarrow$ CP odd states

\rightarrow Lifetime of K_1 and K_2 are different.

Remark: K_1, K_2 are not constrained by CPT!

Discovery of long-lived K_2 at cosmic

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

\rightarrow use lifetime to distinguish the physical states.

$K_S = K_1 \quad \tau_S = 0.89 \cdot 10^{-10} \text{ s} \quad K_S \rightarrow \pi\pi$

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

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

② Prediction of Bell-Mann Pais Theorem: Oscillations

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 oscillations".

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

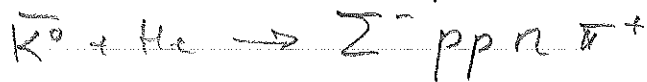
$$P(K^0(t=0) \rightarrow K^0)(t) = \frac{1}{4} \left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2 e^{-(\Gamma_1 + \Gamma_2)/2 \cdot t} \cdot \cos(\Delta m t) \right]$$

$$P(K^0(t) \rightarrow \bar{K}^0)(t) = \frac{1}{4} \left[-2 e^{-(\Gamma_1 + \Gamma_2)/2 \cdot t} \cos(\Delta m t) \right]$$

→ see Figure.

Strangeness oscillations have been observed in 1957 (Lauder et al.)

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



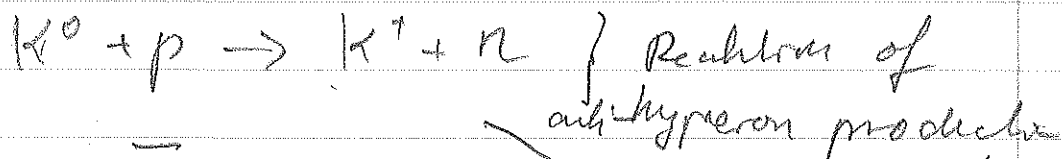
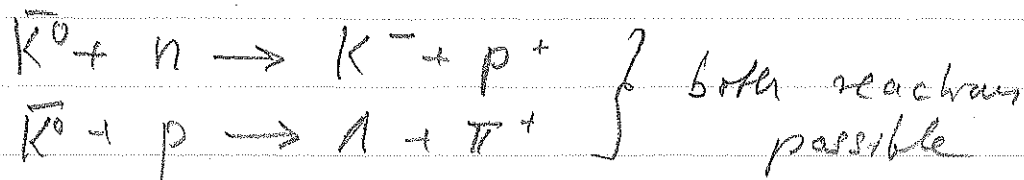
Later the semi-leptonic decay: $K^0 \rightarrow \pi^- e^+ \nu_e$
 $\bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$

was used to resolve the oscillation.

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

③ Reduction of Bell-Mann Pair Theory: Regeneration

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



→ Cross section of \bar{K}^0 with matter } not possible!
 > cross section of K^0 w/ matter

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

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

"regeneration of K_S "

Experimental observation (Miller et al., 1960)

Propane bubble chamber @ distance of $\sim 100 \tau_S$:
 Observation of $K_S \rightarrow \pi\pi$ 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 lose their properties
 → well distinguishable in matter.
 Only the free Hamiltonian (vacuum) makes no diff. between K^0, \bar{K}^0