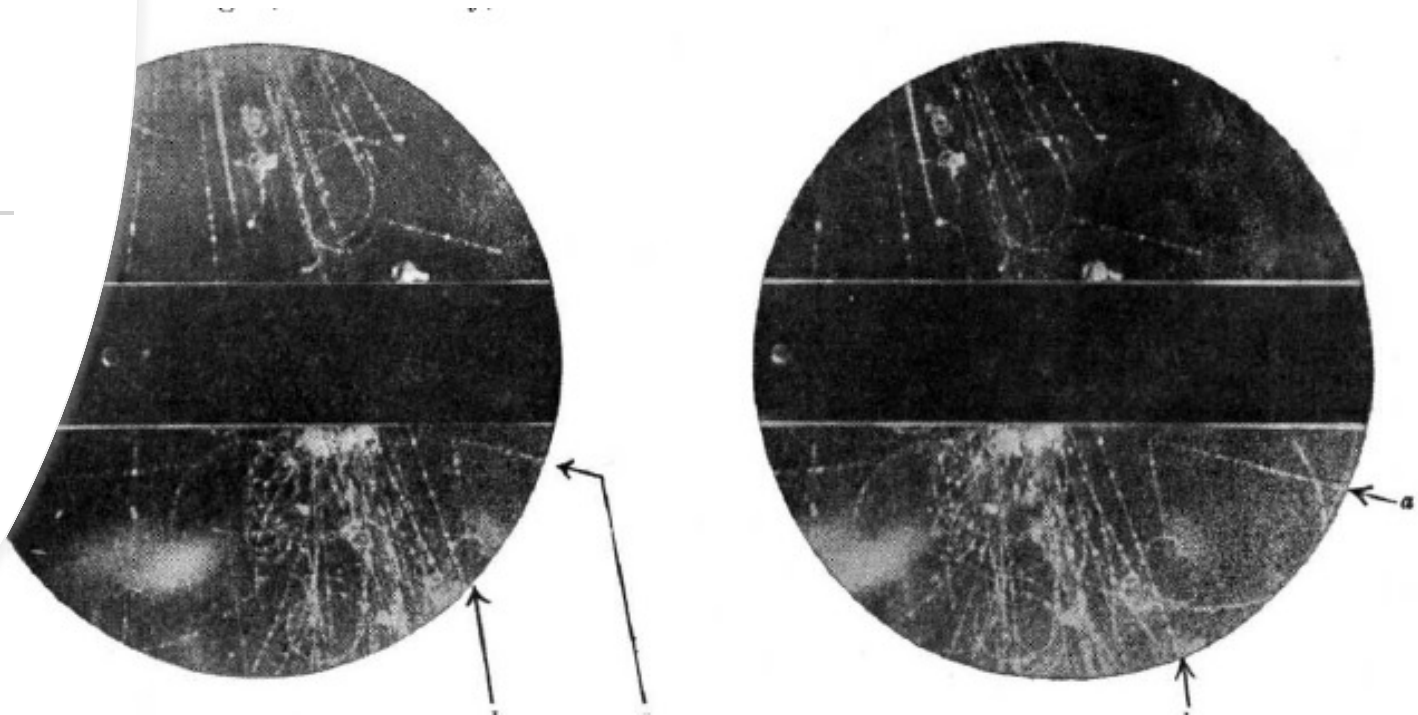
Discovery of Strangeness (1943-1959)

G. Venanzoni

29/4/24

Seminar to the Muon group, Liverpool



Relevant years (40's– 50's)

- 1943: (preliminary) observation of a **K^+** in cosmic rays
- **1947: Discovery of K_0 ($\rightarrow \pi^+ \pi^-$) (V_2^o o θ^o) and K^+ ($\rightarrow$ charged + neutral) in cosmic rays (V particles, forked tracks)**
- 1949: Observation $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ (called τ meson) in cosmic rays
- 1950: Discovery of V_1^o ($\Lambda^o \rightarrow p\, \pi^-$) in cosmic rays
- 1951: Evidence for $K^+ \rightarrow \mu^+$ + *neutral* (called κ decay) in cosmic rays
- 1953: Precise determination of the mass of the V_2^o o θ^o (equal to the mass of τ meson), the setting the stage for the θ τ puzzle and **discovery of parity violation**

Relevant years (40's– 50's)

- 1953: Conference on cosmic rays at Bagneres-de-Bigorre. V_1^o, θ, τ, κ, χ ($K^+ \rightarrow \pi^+ \pi^0$) well established. Analysis presented by R. Dalitz: θ, τ have different parity. Different particles if parity is conserved
- 1953: Cosmotron at BNL started operation with π beam (up to 3.3 GeV), confirming and estending cosmic rays results.
- 1954: Bevatron started operations with proton up to 6 GeV in Berkley. Emulsion technique focused on K^+ (θ^+, χ^+, κ^+) and τ^+. Same mass and lifetime between K^+ and τ^+.
- 1954: G-Stack (for "giant") experiment (15 l of emulsion) on a ballon at an altitude of 27 km for 6 hours provided a clear identification of $K^+ \rightarrow \mu^+\nu$, $K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \pi^0 e^+\nu$)

Relevant years (40's– 50's)

- 1953-59: Evidence for hyperons beside V_1^o (Λ^o): V^+ (Σ^+), V^- (Σ^-) (1953) observed with cosmic rays and at accelerator (cosmotron); V^0 (Σ^0) (1955) at cosmotron and Ξ^0 (1959) at betatron (Ω^- discovered in1964 at AGS providing spectacular confirmation for the baryon classification model (Eightfold way))

- 1954:introduction of the new quantum number (Strangeness) by Gellman and Pais to explain the high production rate (consistent with the strong interaction) and the long lifetimes (consistent with a weak decay) of these " strange" particles. Strangeness is conserved in strong interactions, while is violated in the weak decays

Relevant technologies

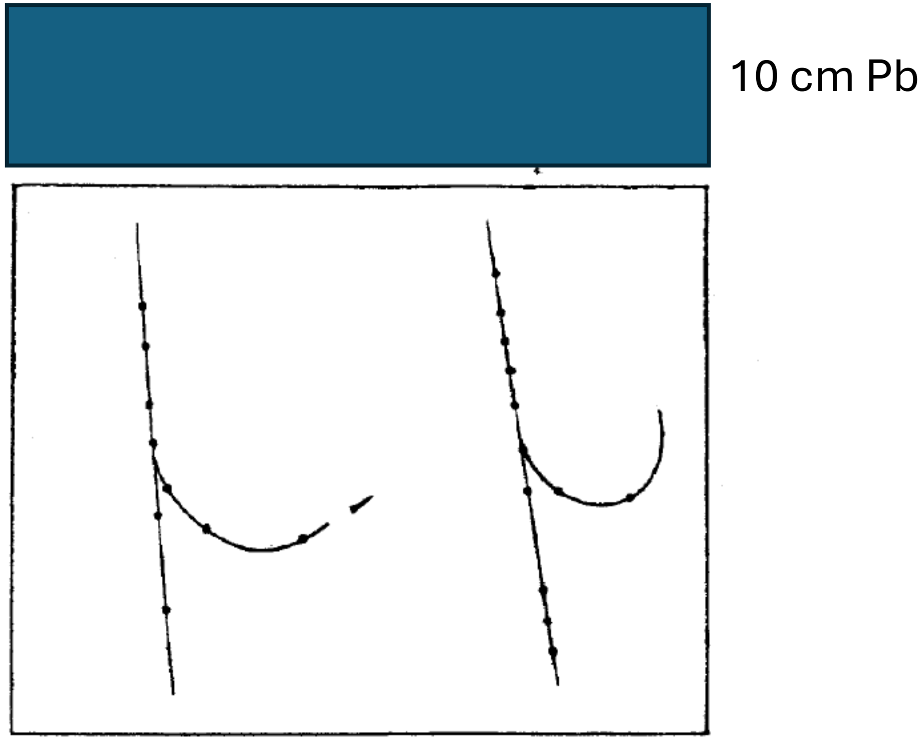
- Cloud/Wilson Chamber & nuclear emulsion (expertise mostly in UK), bubble chamber (invented in 1953 by Gasler)
- Main activity: Bristol, Manchester (cosmic rays); BNL & Berkley (accelerators)

Old Name	New Name
τ	$K_{\pi 3}$: $K^+ \to \pi^+\pi^+\pi^-$
V_1^0	$\Lambda^0 \to p\pi^-$
V_2^0 (θ^0)	$K^0_S \to \pi^+\pi^-$
κ	$K_{\mu 2}$: $K^+ \to \mu^+\nu$
	$K_{\mu 3}$: $K^+ \to \mu^+\pi^0\nu$
χ (θ^+)	$K_{\pi 2}$: $K^+ \to \pi^+\pi^0$
V^+, Λ^+	$\Sigma^+ \to p\pi^0$, $n\pi^+$

L. Leprince-Riguet, M. Lhéritier (1944)

"Existence probable d'une particule de masse 990 m_o dans le rayonnement cosmique"

- Wilson chamber of 75 cm (height) x 15 cm x 10 cm , with B = 2500 G on French Alps (at 1000m altitude).
- An image (out of 10^4) with positive particle ≈ 500 MeV/c momentum producing a secondary ≈ 1 MeV/c momentum
- Assuming elastic scattering on e^-, from scattering angle its mass is 990 $m_e \pm 12\%$ =506+-61 MeV/c^2 (K^+ mass = 493.68 MeV/c2).
- Incompatible with a pion, hardly with a proton (H. Bethe, Phys Rev 70 **821** (1946))

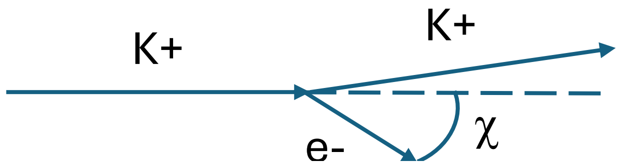


Dessin stéréoscopique de la collision.

L. Leprince-Riguet, M. Lhéritier (1944)

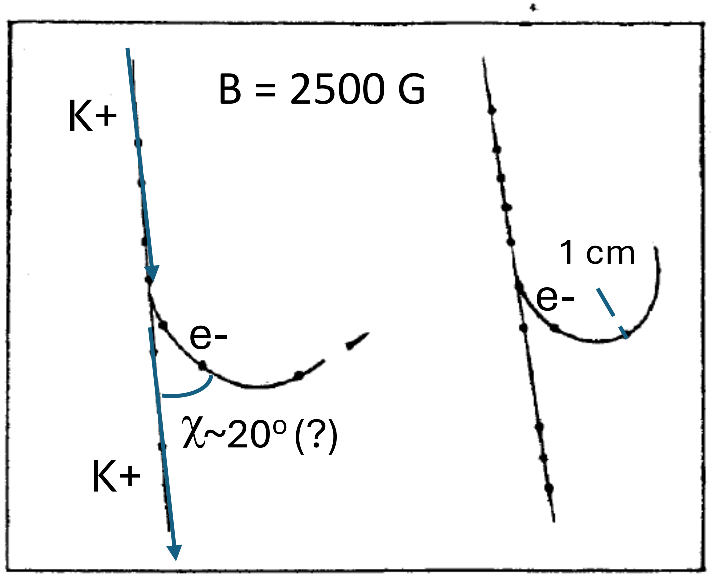
"Existence probable d'une particule de masse 990 m_o dans le rayonnement cosmique"

I tried to replicate the values…



$$M = p\left[\frac{E+m_e}{E-m_e}\cos^2\chi - 1\right]^{1/2}$$

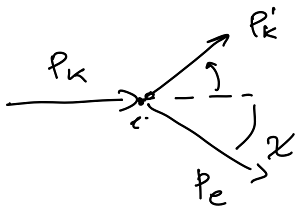
$p = p_K$ incident = 510 MeV (ρ= 680 cm)
$E = E_e \sim 1$ MeV
M ~ 510 MeV (quoted from their paper)



Dessin stéréoscopique de la collision.

Using the current masses in the PDG I got an higher mass (530 MeV) but this could be not a correct interpretation of their data or some wrong assumptions from their calculation (see next slide)

L. Leprince-Riguet, M. Lhéritier (1944)



$\vec{p}_K \cdot \vec{p}_e = |\vec{p}_K||\vec{p}_e| \cos\chi$

$\vec{p}_{K'} = \vec{p}_K - \vec{p}_e$

$|\vec{p}'_K|^2 = |\vec{p}_K|^2 + |\vec{p}_e|^2 - 2\vec{p}_K\cdot\vec{p}_e = |\vec{p}_K|^2 + |\vec{p}_e|^2 - 2|\vec{p}_K||\vec{p}_e|\cos\chi$

$|\vec{p}'_K| = p'_K \quad |\vec{p}_e| = p_e \quad |\vec{p}_K| = p_K$

$p'^2_K = p_K^2 + p_e^2 - 2p_K p_e\cos\chi \to E'^2_K - M^2_K = E_K^2 - M_K^2 + E_e^2 - m_e^2 - 2p_K p_e\cos\chi$

$2p_K p_e\cos\chi = E_e^2 - m_e^2 + E_K^2 - E'^2_K = (E_e - m_e)(E_e + m_e) + (E_K - E'_K)(E_K + E'_K)$

From Energy conservation: $E_K + m_e = E'_K + E_e \to E_K - E'_K = E_e - m_e$

$2p_K p_e\cos\chi = (E_e - m_e)(E_e + m_e) + (E_e - m_e)(E_K + E'_K)$

$2p_K p_e\cos\chi = (E_e - m_e)(E_e + E'_K + m_e + E_K) = 2(E - m_e)(m_e + E_K)$

$E_K + m_e = \frac{p_K p_e\cos\chi}{E_e - m_e} \to \frac{E_K + m_e}{p_K} = \frac{p_e\cos\chi}{E_e - m_e} \to \frac{E_K}{p_K} \simeq \frac{p_e\cos\chi}{(E_e - m_e)}$

$$\frac{E_K^2}{p_K^2} = \frac{p_e^2\cos^2\chi}{(E_e - m_e)^2} \to 1 + \frac{M^2}{p_K^2} = \frac{E^2 - m_e^2}{(E_e - m_e)^2}\cos^2\chi \to 1 + \frac{M^2}{p_K^2} = \frac{(E + m_e)}{(E - m_e)}\cos^2\chi$$

$$\frac{E_K^2}{p_K^2} = \frac{p_e^2\cos^2\chi}{(E_e - m_e)^2} \to 1 + \frac{M^2}{p_K^2} = \frac{E^2 - m_e^2}{(E_e - m_e)^2}\cos^2\chi \to 1 + \frac{M^2}{p_K^2} = \frac{(E + m_e)}{(E - m_e)}\cos^2\chi$$

$$M^2 = p^2\left[\frac{(E + m_e)}{(E - m_e)}\cos^2\chi - 1\right]$$

$$M = p\left[\frac{E + m_e}{E - m_e}\cos^2\chi - 1\right]^{1/2}$$

$$M = 510\left[\frac{1.3 + 0.51}{1.3 - 0.51}\,0.9 - 1\right]^{1/2}$$

$= 530$ MeV (?) probably I got wrong some quantity/assumption

using $\rho_K = 700$ cm and

$p(\text{GeV}) = 0.3\,\rho(\text{m})\,B(\text{T})$

with $\rho B = 1.7\cdot 10^3$ kG·cm

$p(\text{GeV}) = 0.3\cdot 1.7\ \text{T m} = 0.51$ GeV

$\rho_e = 1.6$ cm (?) $\to p_e = \frac{510}{680}\cdot 1.6 = 1.2$ MeV

$E_e = 1.3$ MeV

$\chi = \text{atg}(0.32) = 17.7°$

$\cos^2\chi = 0.91$ (?)

Probably different assumption/calculation

G.D. Rochester, C.C. Butler (1947):

(Manchester)

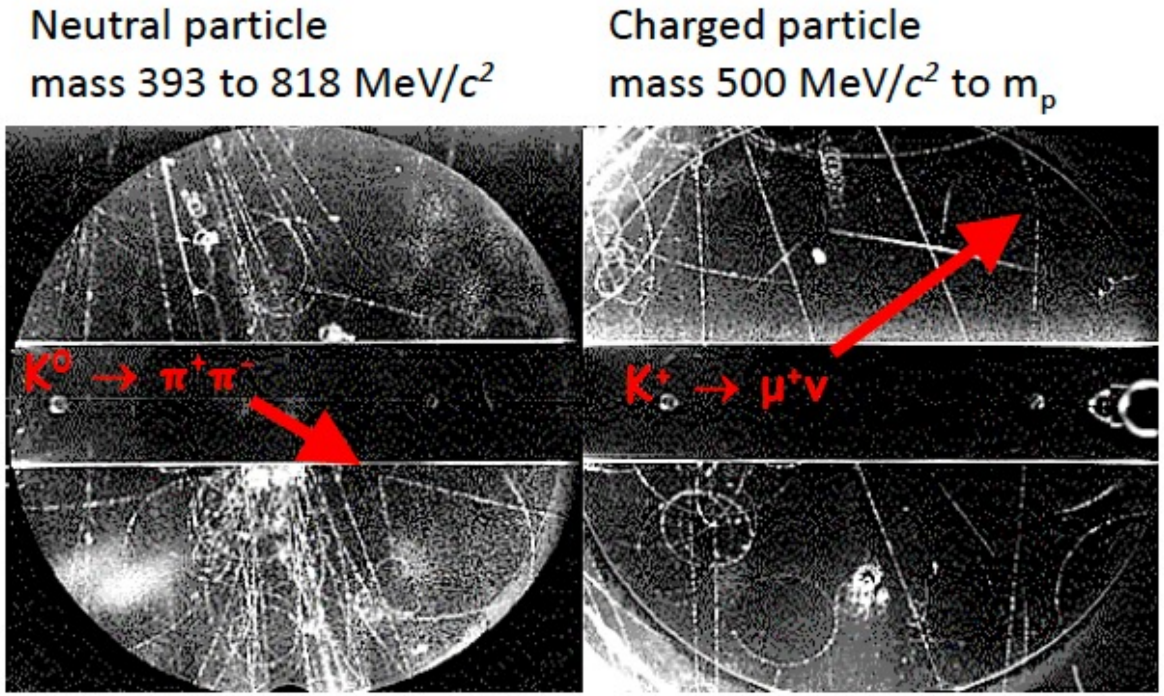
"Evidence for the existence of new unstable elementary particles"

Discovery of "V particles" (Kaons, strange particles)

Cloud chamber on cosmic rays, with a single absorber plate. No electrons or positrons, only penetrating particles. Estimate the mass by energy-momentum conservation (M> 390±77 MeV; M~O(510 MeV))

"V" particles due to the topology (forked) of the tracks

First evidence of "strange" particles

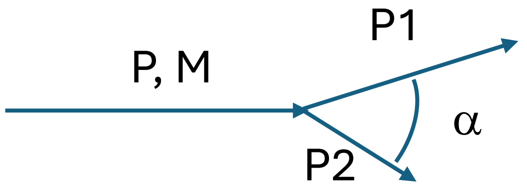


G.D. Rochester, C.C. Butler (1947):

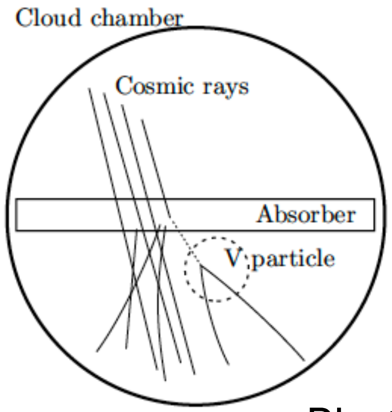
"Evidence for the existence of new unstable elementary particles"

TABLE 1. EXPERIMENTAL DATA

Photo-graph	H (gauss)	a (deg.)	Track	p (eV./c.)	Δp (eV./c.)	Sign
1	3500	66·6	a b	$3{\cdot}4 \times 10^8$ $3{\cdot}5 \times 10^8$	$1{\cdot}0 \times 10^8$ $1{\cdot}5 \times 10^8$	+ −



$$M^2 = m_1^2 + m_2^2 + 2\left(\sqrt{p_1^2 + m_1^2}\sqrt{p_2^2 + m_2^2} - p_1 p_2 \cos\alpha\right)$$



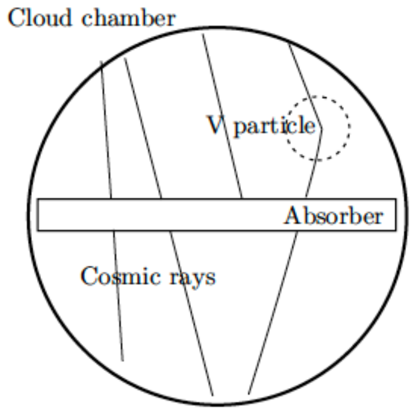
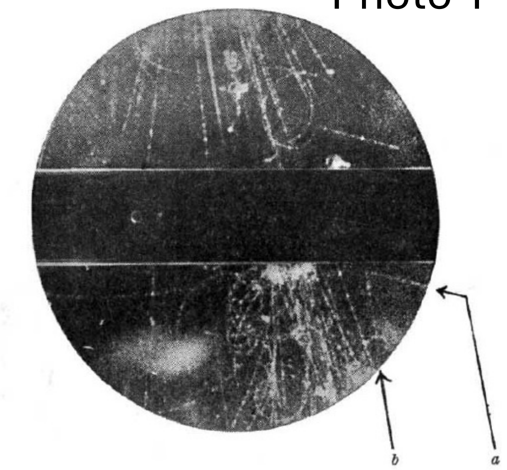


Photo 1



Using Table 1 I compared two hypoteses:

1: θ^0 ($K^o \rightarrow \pi^+\pi^-$) M=470 $\pm$ 80 MeV. (0.3σ from PDG K_0=497.6 MeV)

2: V_1^o ($\Lambda^o \rightarrow p\pi^-$) M=1240 $\pm$ 60 MeV (2σ from PDG Λ^0=1115.7 MeV)

(Thanks Riccardo for the error evaluation)

G.D. Rochester, C.C. Butler (1947):

On ~1000 triggered pictures corresponding to ~1000 nuclear interactions, one could observe the production of a few particles which decayed in few cm.
Assuming a cross section of ~ 1 mb on proton we expect a production in few (2 cm) plate of Pb:

$$L = l\rho N_A \frac{Z}{A} = 2\ cm \times 11.3\ \frac{g}{cm^3} \times 6 \times 10^{23} \times 0.4 \sim 5 \times 10^{24} cm^{-2} = 5 \times 10^{-3} mb^{-1}$$

$$N_{events} = N_{in} \times \sigma\ L = 10^3 \times 1\ mb \times 5 \times 10^{-3}\ mb^{-1} \sim 5$$

Assuming the V-particles travel a few cm with P/M=γβ~2, their lifetime is O(10^{-10} s) (τ=d/(γβc)) typical of weak interactions. Thus we conclude that the decay of V-particles is weak while the production is strong.
This strange property of K mesons and other particles, the hyperons, led to the introduction of a new quantum number, the strangeness, S
Strangeness is conserved in strong interactions, while is violated in the weak decays

R. Brown, U. Camerini, P. H. Fowler, H. Muirehead, C.F. Powell, D. M. Ritson (1949):

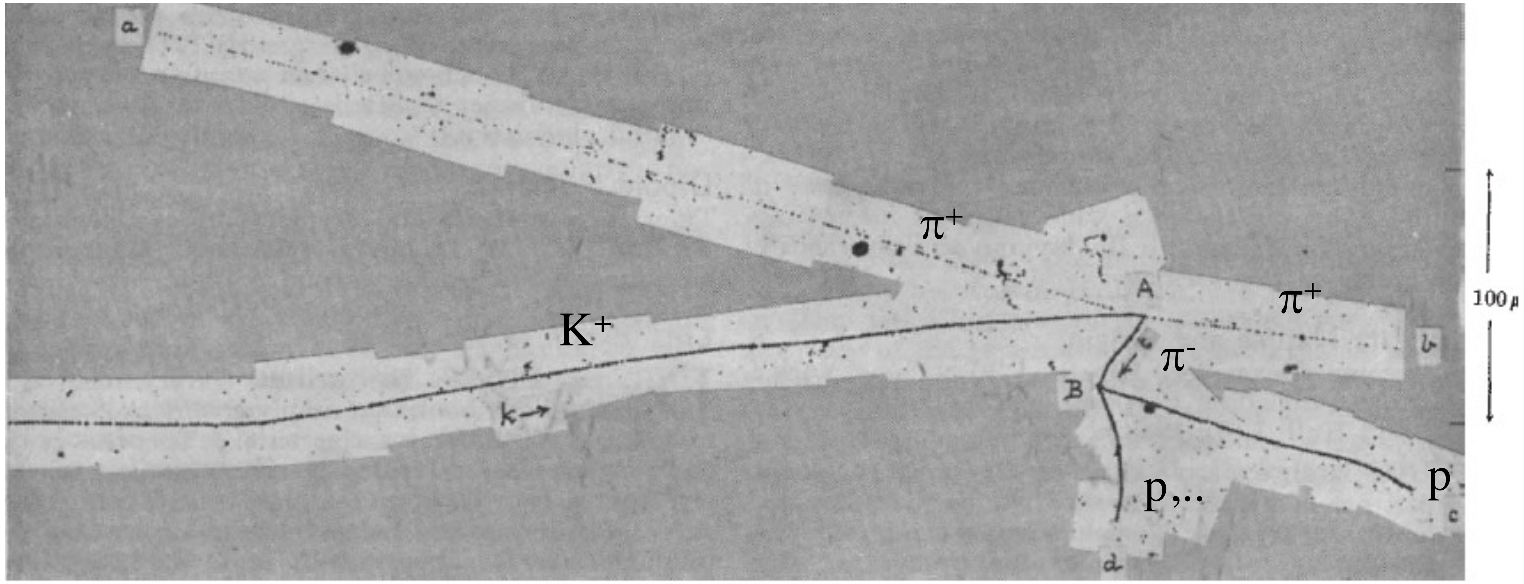
Bristol

"Observations with Electron-Sensitive Plates Exposed to Cosmic Radiation"

M_{K+} =1080 $\pm$ 160 m_e (=552 $\pm$ 81 MeV) obtained by counting the grain per units of length (M_{K+}= 493.677 $\pm$ 0.0016 PDG)

- Track ***t*** is probably a low momentum π^- which has reached it end-of-range and disintigrates against a nucleus giving 2 **p** or heavier particles (c, d)
- The grain-density of track a and b are compatible with $\pi^{\pm}$ or $\mu^{\pm}$
- "There is some support that the three product-particles are π-mesons; but the alternative of one π and two μ or one μ and two π cannot be excluded"

Discovery of τ^+ meson ($K^+ \rightarrow \pi^+ \pi^+ \pi^-$)

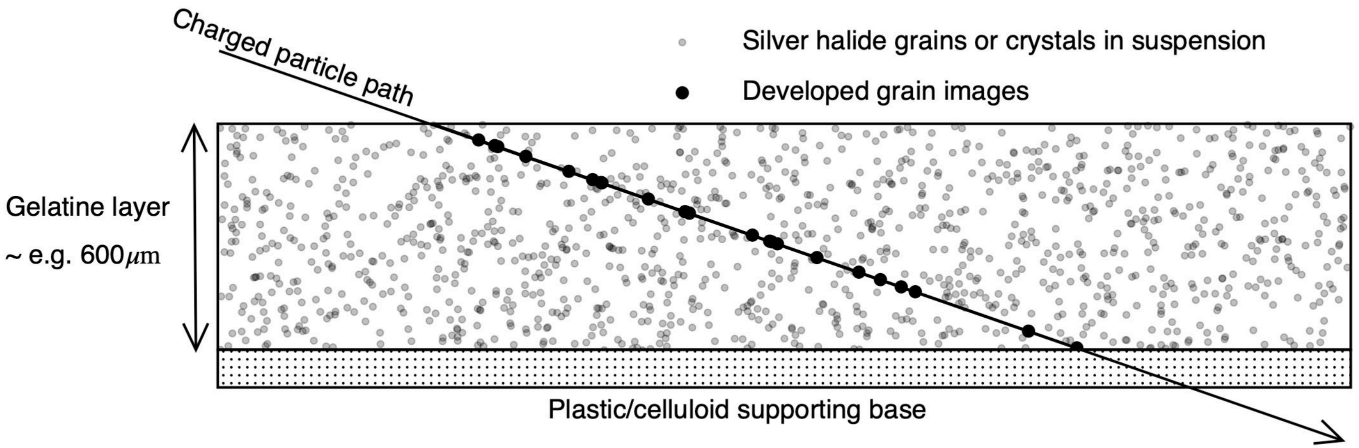


"Stripped" emulsion technique

Nuclear Emulsion

- They are usually made in thin films, from about 20 - 100 μm, of size 50cm x 50 cm, usually monted on glass plates and placed on microscopes stages for examinations

- Silver halide crystals (about 0.3 μm size) embedded in an organic matrix, composed mostly of gelatin with water, glycerol etc…added to form a gel (density~ 1.3 g/ml)



- An ionizing particle crossing a crystal, leaves in a state whereby it develops fast. After the development we are left with a trail of silver grains in a transparent medium

- Use a 1000x microscope to measure the grain density distributions
- Compact object, three dimentional study, records all tracks during its exposure time, good for collecting rare events and cheap (1$ per cm^3) . It needs however a labor intense work to extract and process the information.

C. O' Ceallaigh (1951):

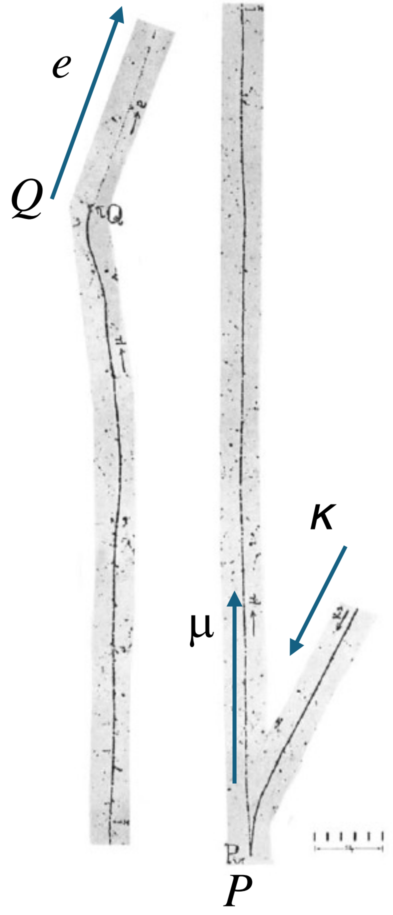
"Masses and Modes of Decay of Heavy Mesons - Part I"

Bristol

emulsion technique

Observation of the κ decay ($K^+ \rightarrow \mu^+\nu$ ($K_{\mu 2}$); $K^+ \rightarrow \mu^+\pi^0\nu$ ($K_{\mu 3}$))

- A κ (K^+) meson stops at P, decaying into a muon and neutrals.
- The muon decays at Q to an electron and neutrals. The muon track is shown in two long sections.
- Note the lighter ionization produced by the electron, contrasted with the heavy ionization produced by the muon near the end of its range.
- The mass of the κ was measured by scattering and grain density to be 562 ± 70 MeV (M_{K+}= 493.677 ± 0.0016 PDG)



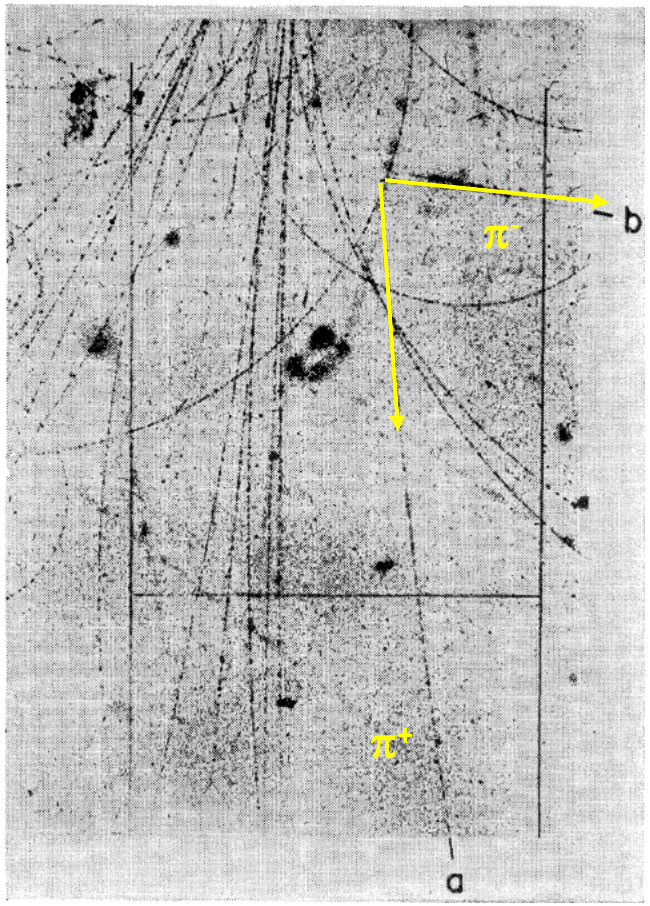
Indiana University

R. W. Thompson, A. V. Buskirk, L. R. Etter, C. J. Karzmark and R. H. Rediker (1953)

"An Unusual Example of V^o Decay"

Determination of the mass of V^0 (θ^0) ($K_0 \rightarrow \pi^+ \pi^-$)

- Magnetic chamber. Looking for forked tracks
- They measure a Q value for the decay of 214 MeV, in good agreement with the present value ($M_K - 2M_\pi = 219$ MeV).
- This indicated that the τ and θ^0 mesons had just about the same mass and set the stage for the famous puzzle about the parities of these particles



$p_{\pi+} = 670 \pm 20$ MeV
$p_{\pi-} = 94 \pm 8$ MeV
$\alpha = 79.2^o \pm 0.4^o$

M_{V0} = **496 $\pm$ 7 MeV** (using eq. Slide 10) to be compared with M_{K0}=497.614 $\pm$ 0.024 MeV from PDG

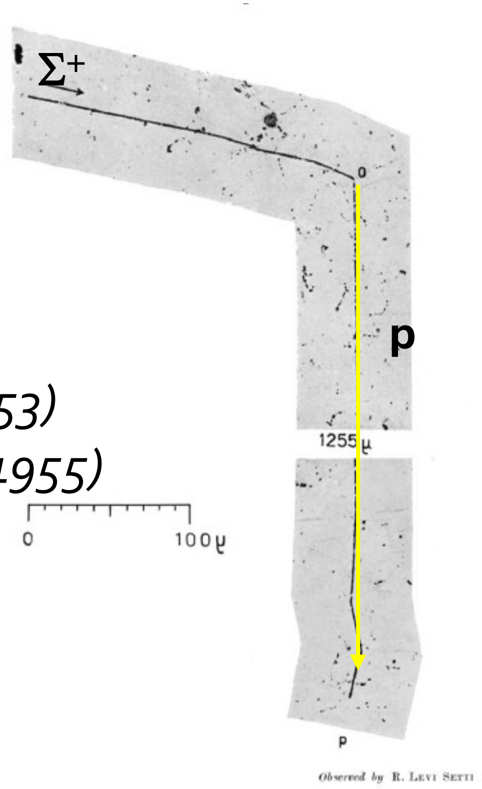
Hyperons (1950 -1964)

Λ^0 *V. D. Hopper and S. Biswas "Evidence Concerning the Existence of the New Unstable Elementary Neutral Particle, Phys. Rev. 80, 1099 (1950)*

$$\Lambda^0 \rightarrow p\, \pi^-$$

S=-1

Σ^+ *A. Bonetti, R. Levi Setti, M. Panetti, and G. Tomasini, "On the Existence of Unstable Particles of Hyperprotonic Mass." Nuovo Cimento, 10, 1 (1953); C. M. York, R. B. Leighton, and E. K. Bjornerud, "Direct Experimental Evidence for the Existence of a Heavy Positive V Particle." Phys. Rev., 90, 167 (1953)*



$$\Sigma^+ \rightarrow p\, \pi^0$$

Σ^- *R. Armenteros et al., "The Properties of Charged V Particles." Phil. Mag., 43, 597 (1952); C. D. Anderson et al., "Cascade Decay of V Particles." Phys. Rev., 92, 1089 (1953)*

Σ^0 *W. D. Walker, " $\Lambda^0 - \theta^0$ Production in π^- p Collisions at 1 BeV." Phys. Rev., 98, 1407 (1955)*

$$\pi^- + p \rightarrow K^0\, \Sigma^0 (\rightarrow \Lambda^0\, \gamma)$$

Ξ^- *E.W. Cowan, "A V-Decay Event with a Heavy Negative Secondary, and Identification of the Secondary V-Decay Event in a Cascade." Phys. Rev., 94, 161 (1954)*

S=-2

$$\Xi^- \rightarrow \Lambda^0\, \pi^-$$

Ξ^0 *L. Alvarez et al. , "Neutral Cascade Hyperon Event." Phys. Rev. Lett., 2, 215 (1959)*

$$K^- + p \rightarrow K^0\, \Xi^0 (\rightarrow \Lambda^0\, \pi^0\,)$$

S=-3

Ω^- *V. E. Barnes et al., "Observation of a Hyperon with Strangeness Minus Three." Phys. Rev. Lett., 12, 204 (1964)*

$$K^- + p \rightarrow K^+ K^-\, \Omega^- (\rightarrow \Xi^0\, \pi^0\,)$$

W. B. Fowler, R. P. Shutt, A. M. Thorndike, W. L. Whittemore (1954):

BNL

"Production of Heavy Unstable Particles by Negative Pions"

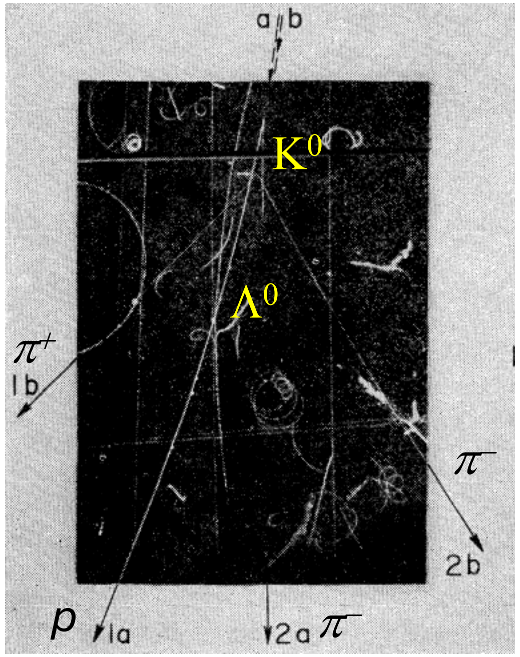
Production of associated $\Lambda^0\theta^0(K^0)$, $\Lambda^-(\Sigma^-)K^+$ at accelerator

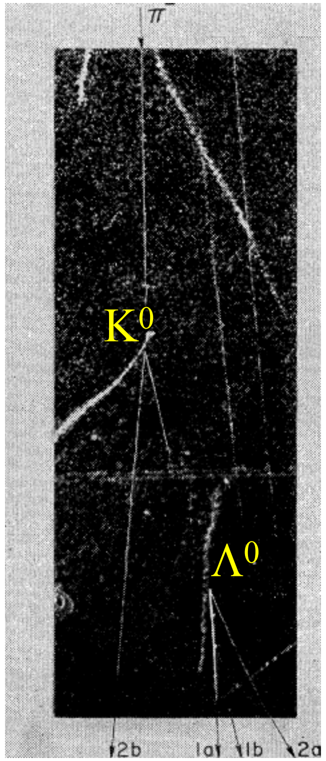
$$\pi^- + p \rightarrow \Lambda\,(\rightarrow p\pi) + K$$

- 1.5 GeV p^- beam at Cosmotron BNL
- Cloud chamber filled with $\mathbf{H_2}$ (!) at 20 atm with B= 10 kG
- σ ~ 1 mb; lifetime of Λ, K $10^{-9} - 10^{-10}$ s
- Λ,K produced in association, "double production process"
- They were copiously produced in association by the strong interaction. Their lifetime should have been orders of magnitude shorter if the decay was mediated by the strong interaction → Weak decay

→ Gell-Mann & Pais: the new unstable particles possess a new quantum number "strangeness" conserved in strong interaction , but not in the weak decay

$$\pi^- + p \rightarrow \Lambda^0\,(\rightarrow p\pi^-) + K^0\,(\rightarrow \pi^+\pi^-)$$





π^- $p\ \pi^+$ π^-

τ_{K0}~0.9×10^{-10} τ_Λ~2.6×10^{-10}

Strangeness (1954)

VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

ome properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. ccording to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special e to charge conjugation invariance. The application of such invariance in familiar instances is in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under on, the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each ciated with a different set of decay modes, and that no more than half of all θ^0's undergo the cay into two pions. Some experimental consequences of this picture are mentioned.

M. Gell-Mann

A. Pais

Strangeness (1954)

M. Gell-Mann, A. Pais, Phys. Rev. 97 (1955) 1387

M. Gell-Mann (1929-)

A. Pais (1918-2000)

- Each strongly interacting particle has an **additive** quantum number called **strangeness**. For the old particles (pion and nucleon) the strangeness, S is 0. For the K^+ the strangeness is $+1$, while for the and Λ and Σ's it is -1. K^0 has $S = +1$
- Pairs of mesons with identical masses but opposite electric charges are antiparticles of each other, just as the positron is the antiparticle of the electron. Each antiparticle is assigned the opposite strangeness from the particle. Thus the K^- has strangeness −1, as $\overline{K^0}$.
- Strange particles are produced (by strong int.) conserving S which leads to the idea of associated production: strange particles are always produced in pairs: $\Lambda(S=-1)$+K $(S=1)$, K^0 $(S=1)+\overline{K^0}(S=-1)$,. . . For instance:

$$\pi^- + p \to \Lambda^0 K^0$$

S = 0 $\quad \to \Sigma^- K^+ \quad$ S = -1 + 1 =0

$\not\to \Sigma^+ K^- \quad$ S = -1 - 1 = -2

$\not\to K^+ K^+ \pi^- \pi^- n \quad$ S = 1 + 1 = 2

Particle	S
p, n, π	0
$K^+,\ K^0$	1
$K^-,\ \bar{K}^0$	-1
Λ, Σ	-1
$\bar{\Lambda}, \bar{\Sigma}$	1

- An important consequence of the fact that K mesons carry strangeness, a new additive quantum number, is that the K^0 and $\overline{K^0}$ meson are distinct particles (different for example from π^0,γ,η)
- An apocryphal story says that upon hearing of this hypothesis, Fermi challenged Gell-Mann to devise an experiment which shows an observable difference between the K^0 and the $\overline{K^0}$. We don't know what Gell-Mann answered, but today we know that it is trivial to do so. For example, the process $p\bar{p} \rightarrow \pi^- K^+ \overline{K^0}$, produces $\overline{K^0}$ (S=-1) with a K^+ (S=1) while $p\bar{p} \rightarrow \pi^+ K^- K^0$ a K^0 (S=1) with a K^- (S=-1) . So the presence of a K^+ (K^-) "tag" the presence of $\overline{K^0}$(K^0).

- Another of Fermi's question was:
  - if you observe a $K\rightarrow 2\pi$ decay, how d o you tell whether it is a K^0 or a $\overline{K^0}$? The answer here is complicated and we will discuss this in another seminar

Today view: Quark and flavour

Today we describe these properties in terms of quarks with different "flavours", first suggested in 1964 independently by Gell-Mann and Zweig reformulating the SU(3) flavor, approximate, global symmetry. The "normal particles" are bound states of quarks: q$\bar{q}$, the mesons, or qqq, baryons, where:

$$q = \begin{pmatrix} u \\ d \end{pmatrix} = \begin{pmatrix} \text{up} \\ \text{down} \end{pmatrix}$$

$$K^0 = d\bar{s} \qquad \overline{K^0} = \bar{d}s$$

$$K^+ = u\bar{s} \qquad K^- = \bar{u}s$$

$$S = +1 \qquad S = -1.$$

$\Lambda^0 =$ uds $\quad \Sigma^{0,+,-} =$ uds, uus, dds

$\Xi^{0,-} =$ uss,dss

$\Omega^- =$ sss

The assignment of negative strangeness to the s quark is arbitrary but maintains today the convenient original assignment of positive strangeness for K^0, K^+ and negative for the Λ and Σ hyperons and for $\overline{K^0}$ and K^+.

• From the discovery of Kaons and strangeness:

- P, CP violation
- Eightfold way (classification of mesons and baryons) → quarks
- GIM mechanism → charm quark

(LIGHT) MESONS

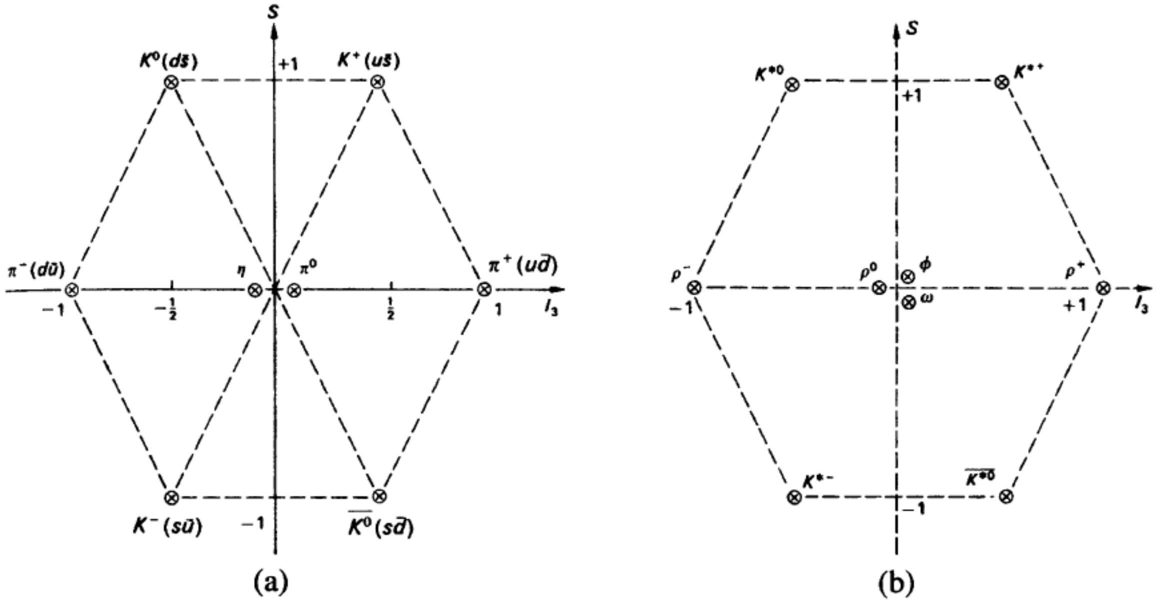


Fig. 4.14. (a) The lowest-lying pseudoscalar meson states ($J^P = 0^-$). Quark flavour assignments are indicated. (b) The vector meson nonet ($J^P = 1^-$). The quark assignments are the same as in (a).

• From the discovery of Kaons and strangeness:

- P, CP violation
- Eightfold way (classification of mesons and baryons) → quarks
- GIM mechanism → charm quark

Baryons

Octet (S=1/2)

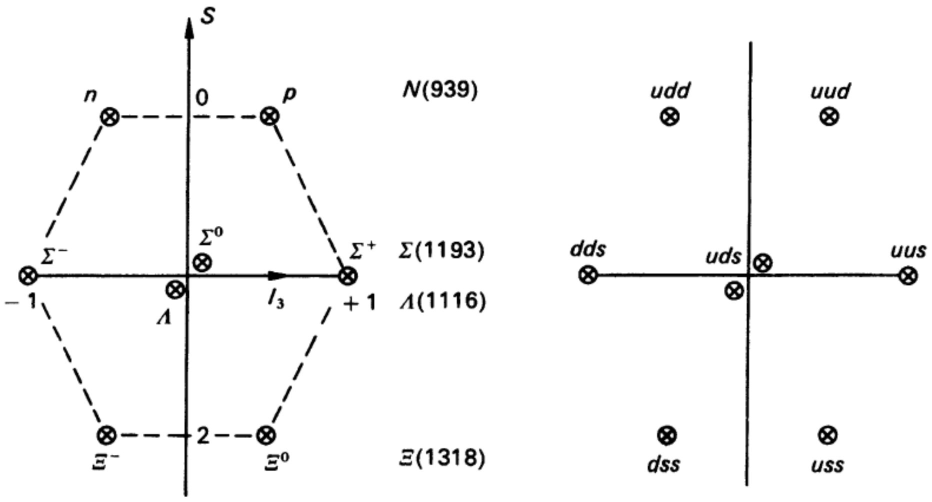


Fig. 4.13. The baryon octet with spin-parity $\frac{1}{2}^+$. The observed states are given on the left, and quark flavour assignments on the right.

Decuplet (S=3/2)

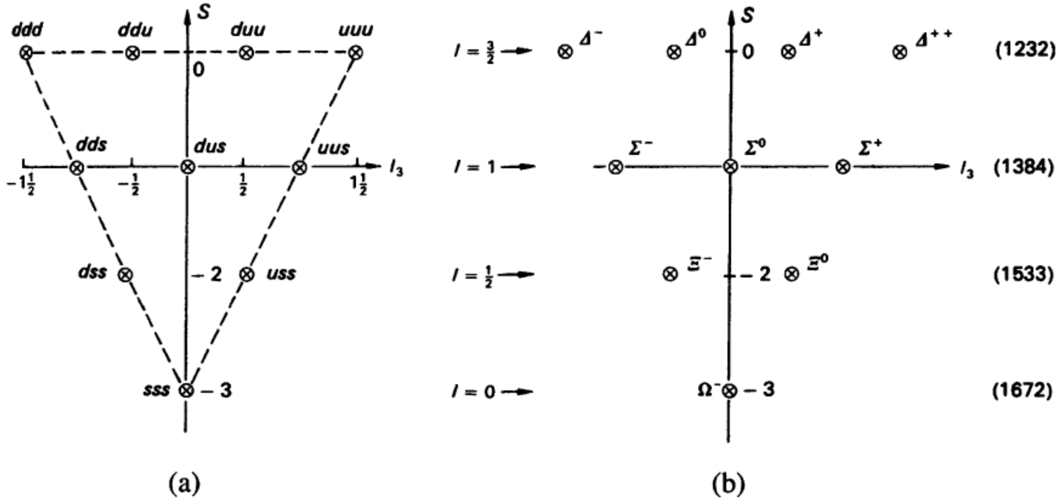


Fig. 4.10. (a) Quark label assignments in the baryon decuplet. (b) The observed decuplet of baryon states of spin-parity $\frac{3}{2}^+$. The mean mass of each isospin multiplet is given in parentheses.

We will see this in a next seminar

END