The Development of Particle Physics

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Previous lecture

- New unstable particles discovered in 40s-50s.
- First hyperons (particles heavier than neutron) found.
- Strange behaviour: produced in strong interactions, decaying to strongly interacting particles, but having long lifetime - typical to weak interactions.
- Hypotheses by Pais and Gell-Mann:
  - A new quantum number - strangeness.
  - Associated production of strange particles.
  - Weak interactions (decays) violate strangeness conservation law.

Resonances and quark model

- Resonances.
- SU(3) symmetry.
- Quark model.

Resonances

- Most of the unstable particles discovered in 1950s have **lifetimes of about 10^{-10} s or more**. Their tracks (if they were not neutral) were clearly seen in the emulsions and cloud chambers.
- The development of particle accelerators and the measurement of interaction cross-sections revealed new particles in the form of ***resonances***.
- **Resonances are the particles with very short lifetimes (of the order of 10^{-24} s)**.
- For resonances **Heisenberg's uncertainty principle** can be used to determine the relation between the lifetime and width of the resonance:

$$\Delta E \Delta t \approx \hbar$$

The first resonance

- First evidence for resonance behaviour of the cross-section was discovered by **H.Anderson, E.Fermi et al.** at Chicago cyclotron in **1952**.
- They investigated the reactions:

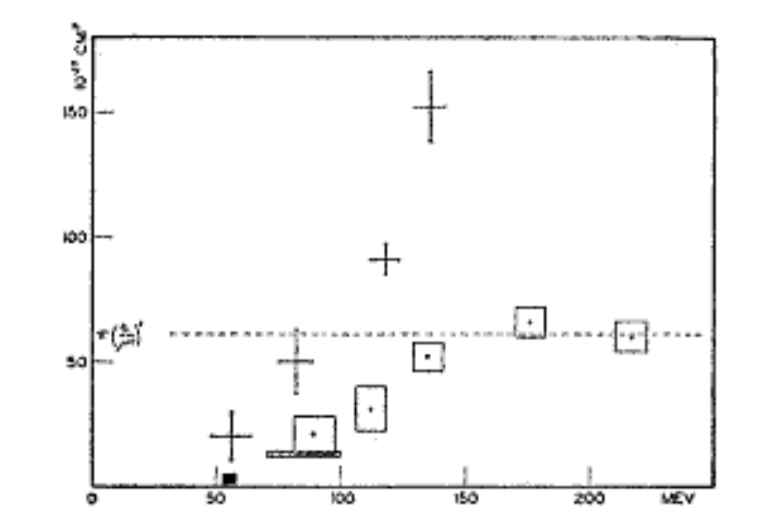
(1) $\pi^+ p \rightarrow \pi^+ p$ - elastic π^+ scattering

(2) $\pi^- p \rightarrow \pi^0 n$ - charge exchange scattering

(3) $\pi^- p \rightarrow \pi^- p$ - elastic π^- scattering

and found that cross-section (1) is the largest, while (3) is the smallest (see graph).

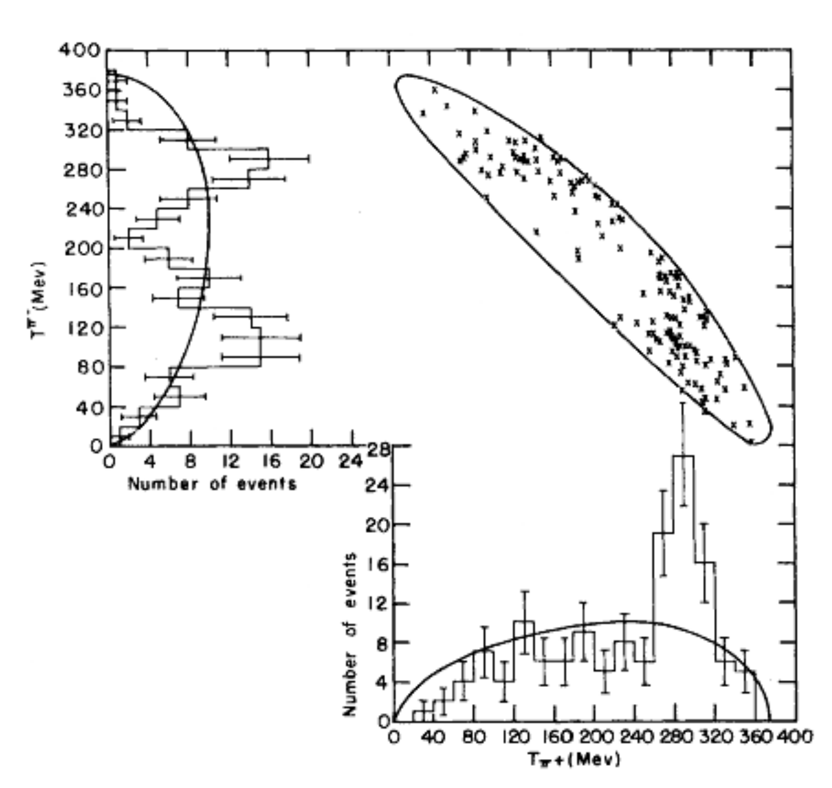
- The data did not go up to high energies to show clear resonance shape.



Resonance in the $\Lambda\ \pi$ system

- In **1960 Alston et al.**, working with K^- beam and bubble chambers at the Bevatron found a resonance in the $\Lambda\ \pi$ system with I=1, now known as the Σ(1385).
- They studied the reaction

  $K^- p \rightarrow \Lambda\ \pi^+ \pi^-$ and found that it went through resonance production Y^{*+} or Y^{*-} that decayed into $\Lambda\ \pi^+$ or $\Lambda\ \pi^-$. For three particle final state a Dalitz plot was used. In the absence of dynamical correlations (constant matrix element), a uniform distribution of points should be seen. The data clearly showed resonance production.



Dalitz plot with invariant masses

At present the invariant masses of the pairs of particles are plotted in Dalitz plots instead of kinetic energies:

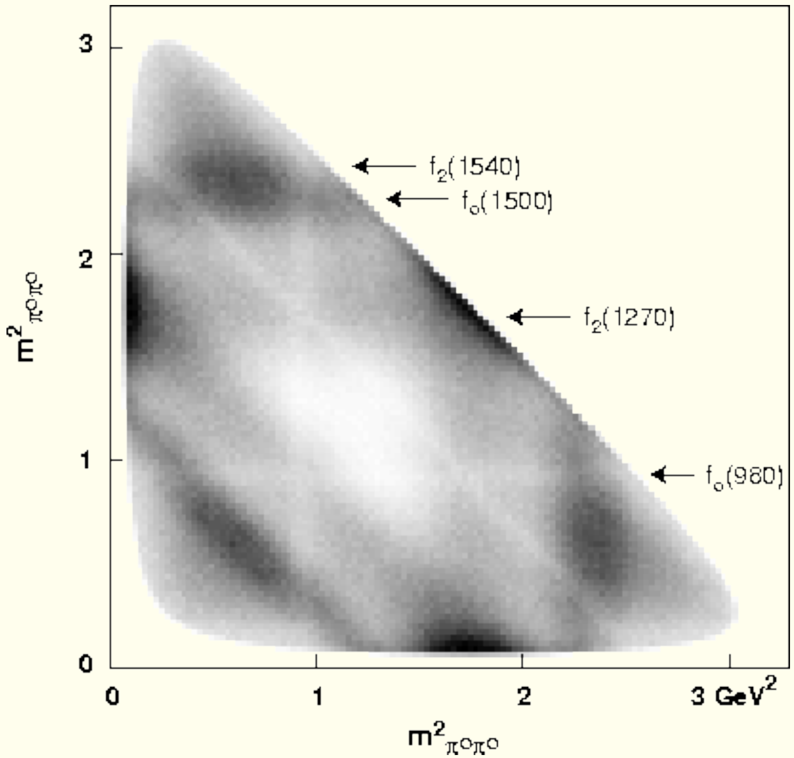
$$M_{12}^2=(p_1+p_2)^2=(E_1+E_2)^2-(\mathbf{p_1}+\mathbf{p_2})^2$$

The graph shows a Dalitz plot for the annihilation process

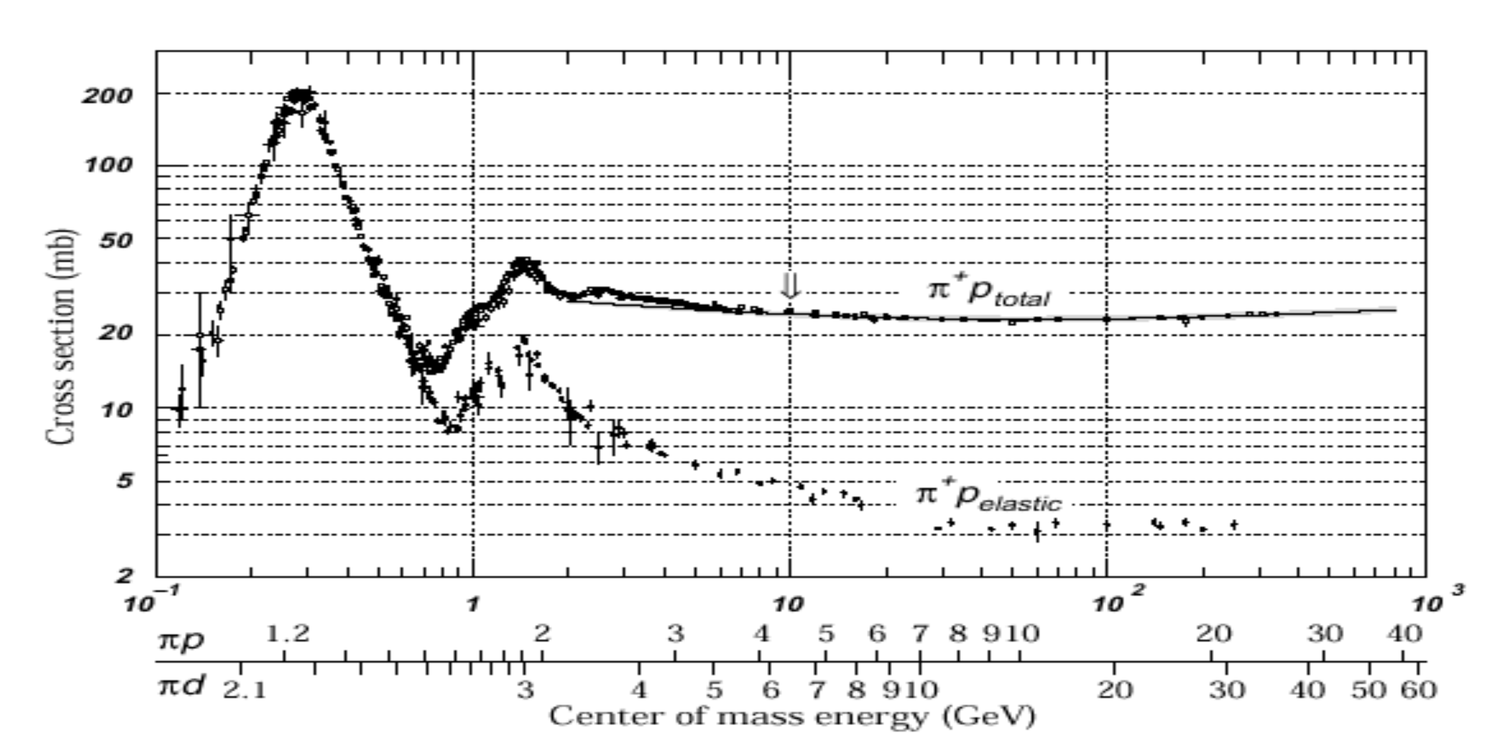
$$p+\overline{p}\rightarrow\pi^0+\pi^0+\pi^0$$

an example taken from the Crystal Barrel experiment.

R. Landua, New Results in Spectroscopy, 28th International Conference on High Energy Physics, 1996.



Cross-section of the $\pi^+ p$ scattering



- Recent measurements of the $\pi^+ p$ scattering cross-section with I=1/2 resonances: Δ (1232), Δ (1920), Δ (2400).

Spectrum of resonances

- Over the years more and more resonances were discovered and interesting regularities in the resonance spectrum became apparent.
- Often a particular set of quantum numbers for isospin and strangeness, such as for the pion (I=1, S=0) and the kaon (I=1/2, S=1) are duplicated by particles with higher masses and spins.
- The higher-mass versions of the quantum numbers generally decay very quickly back down to the least-massive particle with those particular numbers, through the strong interactions. The least-massive versions can then decay more slower by weak force, violating quantum number conservation.

	I	*S*	*Mass*	*Spin*	*Decay*	*Force*		*I*	*S*	*Mass*	*Spin*	*Decay*	*Force*
π	1	0	140	0	$\mu\nu$	*weak*	K	1/2	1	494	0	$\mu\nu$	*weak*
ρ	1	0	768	1	$\pi\pi$	*strong*	K^*	1/2	1	892	1	$K\pi$	*strong*
a_2	1	0	1320	2	$\rho\pi$	*strong*	K_2^*	1/2	1	1425	2	$K\pi$	*strong*
ρ_3	1	0	1690	3	4π	*strong*							

Nuclear democracy

- The term **"resonance"** is applied to the produced states which **decay strongly (very short lifetime)**. The states which decay weakly (like Λ) are called **"particles" (relatively long lifetime)**.
- The difference is somewhat artificial. Which state decays weakly and which decays strongly depends on the masses of the particles involved.
- The ordering of the particles by mass may not be fundamental.
- **Geoffrey Chew** proposed the concept of **"nuclear democracy"** - **equality of particles and resonances**. Resonance K^* is regarded as fundamental as the K itself, even though its lifetime is 10^{14} times shorter.

SU(3) symmetry

- With more and more particles discovered, the problem of their classification arose. This was done by implementing the **new symmetry *SU*(3) - *Special Unitary group* of dimension 3 (3-dimensional space)**.
- Particles can form **multiplets**. In **1961 M. Gell-Mann** and (independently) **Y. Ne'eman** proposed a scheme in which **each *SU*(3) multiplet** must be made of particles sharing **a common value of spin and parity**.
- The basic entity of the model was **the octet** (eight particles). All particles and resonances were to **belong either to octets, or to multiplets** that could be made by combining octets. The rule for combining isospin multiplets follow the law of addition of angular momentum.
- **For *SU*(3) only multiplets with size 1, 8, 10 and 27 can occur**.

SU(3) multiplets

On the graph the horizontal direction measures the 3rd component of isospin, the vertical axis measures the hypercharge, $Y=B+S$.

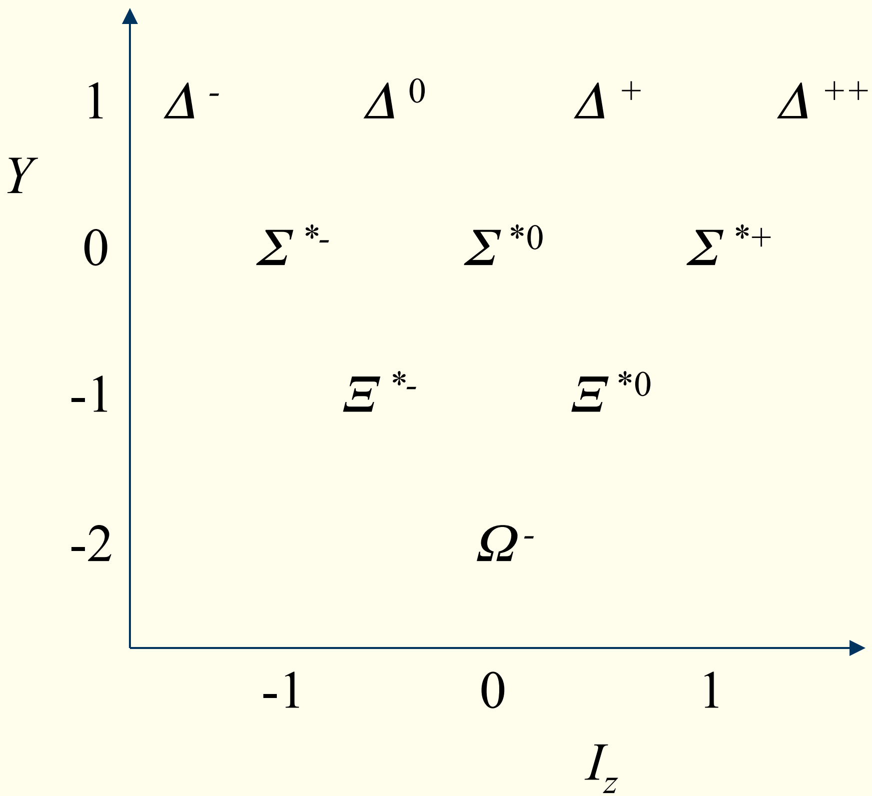
Baryon octet has $J^P=1/2^+$ and contains isodoublet of nucleons, isotriplet Σ, isodoublet Ξ, and isosinglet Λ. Octet of pseudoscalar mesons $J^P=0^-$ contains pions, kaons and η, that was found according to the model predictions.

Y \ I_z	-1		0		1
1		n		p	
0	Σ^-		Σ^0, Λ		Σ^+
-1		Ξ^-		Ξ^0	

Y \ I_z	-1		0		1
1		K^0		K^+	
0	π^-		π^0, η		π^+
-1		K^-		$\bar{K}^0$	

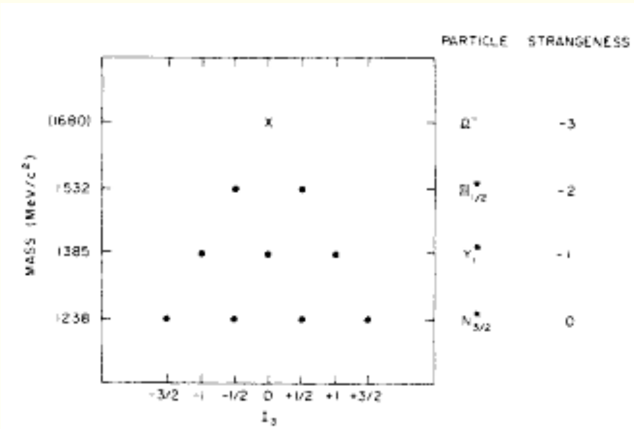
SU(3) multiplets

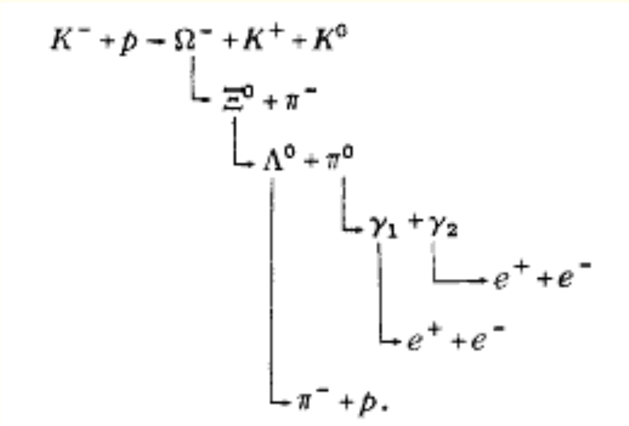
Baryon decuplet with $J^P = 3/2^+$



- The Ω^- was not known at that time yet. It was predicted on the base of $SU(3)$ symmetry in **1962**.
- It was discovered in **1964** in bubble chamber experiment at Brookhaven, convincing the world of the validity of $SU(3)$.

Discovery of Ω⁻





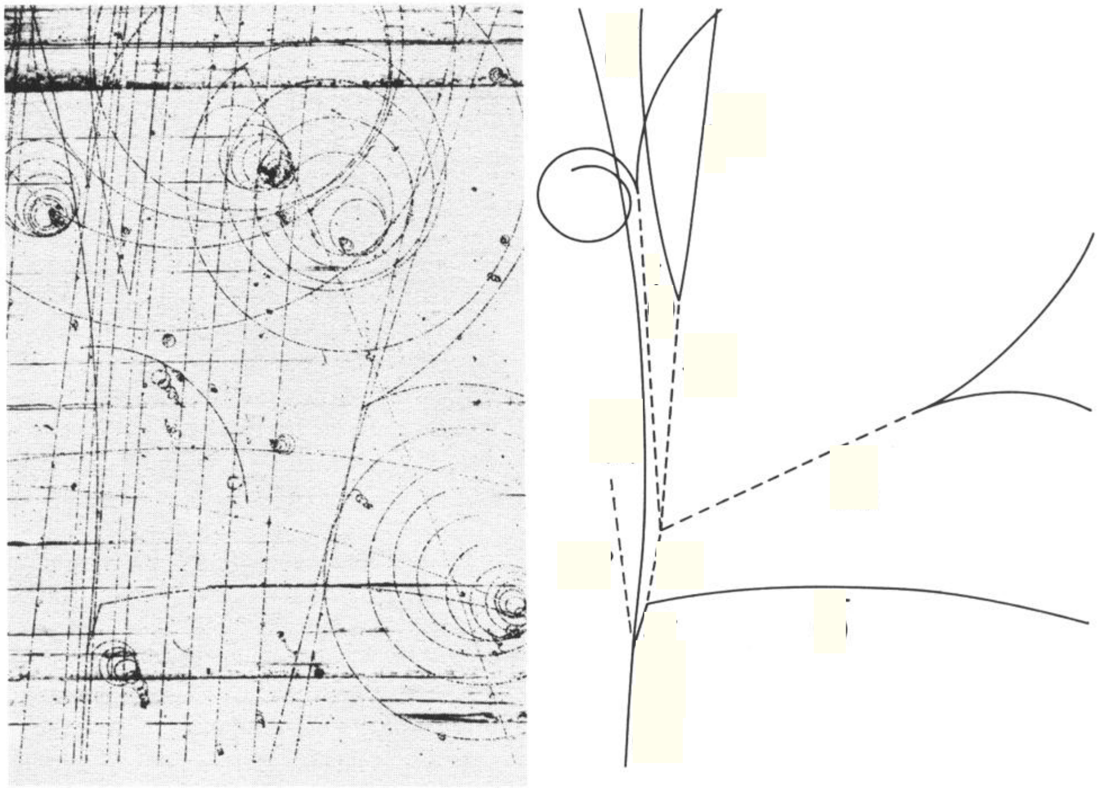
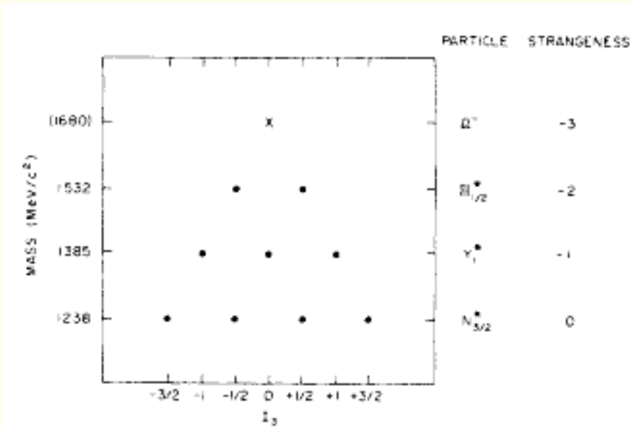
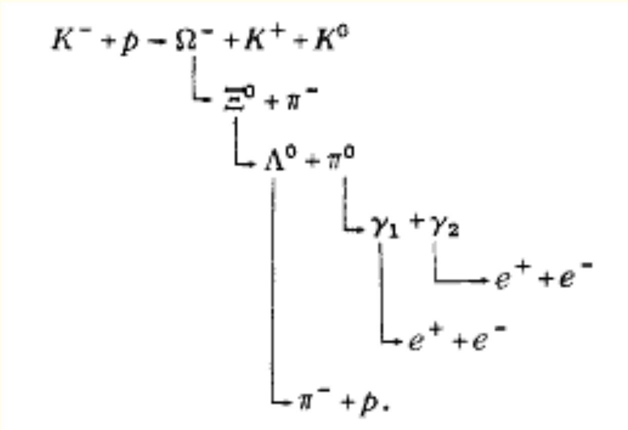


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

Discovery of Ω^-





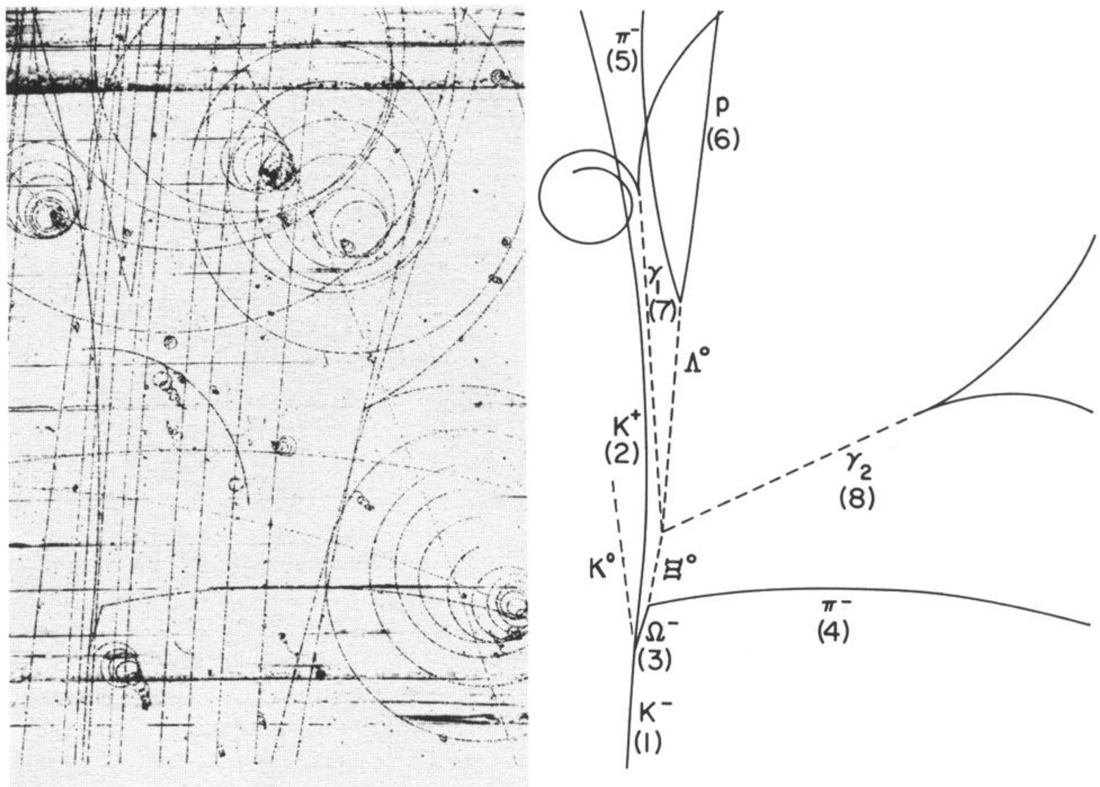
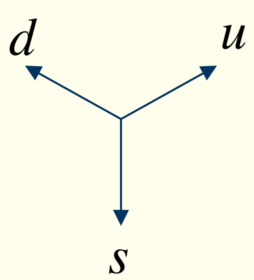
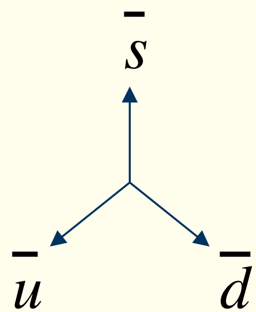


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

Quarks

- A clearer understanding of SU(3) symmetry emerged when **Gell-Mann** and independently, **G. Zweig** proposed that hadrons were built from **three basic constituents - *quarks*.**
- **Baryons consist of 3 quarks: *u* (*up*), *d* (*down*), *s* (*strange*)**.
- **Mesons consist of quark-antiquark pairs**.
- Quarks are required to have **fractional charge: ±1/3 or ±2/3**.

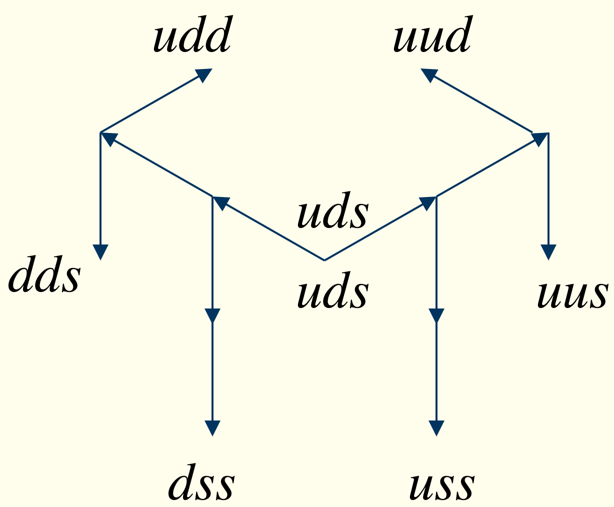




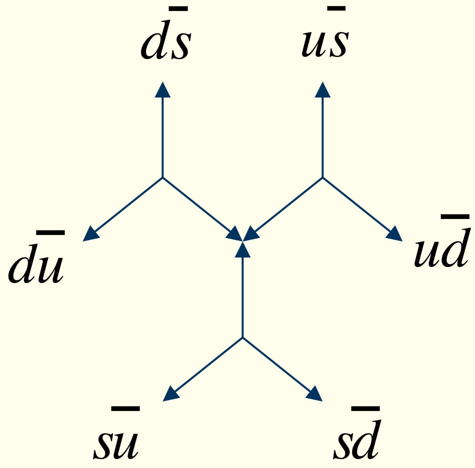
Quarks can be presented in a vector form. Then, their combinations are the sums of vectors.

Quark content of SU(3) representations

Baryon octet



Meson octet



The quark contents of the particles in the middle are:

$$\frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$$

$$\frac{1}{\sqrt{6}}(d\bar{d} + u\bar{u} - 2s\bar{s})$$

Pseudoscalar mesons

Multi-plet	I	I_3	S	Meson	Quarks	Decay	Mass, MeV
	1	1	0	π^+	$u\bar{d}$	$\pi^\pm \to \mu\nu$	140
	1	-1	0	π^-	$d\bar{u}$		
	1	0	0	π^0	$1/\sqrt{2}(d\bar{d}-u\bar{u})$	$\pi^0 \to 2\gamma$	135
Octet	1/2	1/2	+1	K^+	$u\bar{s}$	$K^+ \to \mu\nu$	494
	1/2	-1/2	+1	K^0	$d\bar{s}$	$K^0 \to \pi^+\pi^-$	498
	1/2	-1/2	-1	K^-	$u\bar{s}$	$K^- \to \mu\nu$	494
	1/2	1/2	-1	$\bar{K}^0$	$d\bar{s}$	$\bar{K}^0 \to \pi^+\pi^-$	498
	0	0	0	η	$1/\sqrt{6}(d\bar{d}+u\bar{u}-2s\bar{s})$	$\eta \to 2\gamma$	549
Singlet	0	0	0	η'	$1/\sqrt{3}(d\bar{d}+u\bar{u}+s\bar{s})$	$\eta' \to \eta\pi\pi$ $\to 2\gamma$	958

Summary

- With the development of accelerators new particles (resonances) with very short lifetimes were found.
- **Gell-Mann** proposed a new classification scheme for elementary particles based on SU(3) symmetry.
- This scheme finally led to the quark hypothesis.

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