Introduction to Elementary Particle Physics

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Elementary Particle Physics

Lecture 9 and 10: Esfand 18 and 20, 1397

1397-98-II

Leptons and quarks

Lectrue 9

Leptons

Leptons							
Lepton Flavor (charged and neutral leptons)	**Symbol**	**Mass in MeV**	**Charge**	**Baryonic Number**	**No color charges**	**Type of interactions or decays**	**Lepton flavor number**
Electron	e^-	0.511	-1	0	0	Electromagnetic & Weak interactions	L_e=+1
Muon	μ^-	106	-1	0	0		L_μ=+1
Tauon	τ^-	1777	-1	0	0		L_τ=+1
Electron neutrino	ν_e	$< 2 \times 10^{-6}$	0	0	0	Only weak interactions	L_e=+1
Muon neutrino	ν_μ	< 0.2	0	0	0		L_μ=+1
Tau Neutrino	ν_τ	< 18	0	0	0		L_τ=+1
The corresponding antiparticles to e^-, μ^-, τ^-, and to all neutrinos				0	0		-1 for all antileptons

Remarks:

- **Lepton flavor number conservation:**
  - Lepton flavor number of leptons $L_e, L_\mu, L_\tau = +1$
  - Lepton flavor number of antileptons $L_e, L_\mu, L_\tau = -1$
    Assumption: No neutrino mixing

  Ex.: $\pi^+ \to \mu^+ + \nu_\mu, \quad n \to p + e^- + \bar{\nu}_e, \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

  But, $\mu^+ \to e^+ + \gamma$ is forbidden

- **Two other quantum numbers for leptons**
  - **Weak hypercharge** Y_W**:** It is 1 for all **left-handed** leptons
  - **Weak isospin** T_3**:**

    For each lepton generation, for example $\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \to T_3 = \begin{pmatrix} -\frac{1}{2} \\ +\frac{1}{2} \end{pmatrix}$

- **Type of interaction:**
  - **Charged leptons** undergo both EM and weak interactions
  - **Neutrinos** interact only weakly

Quarks

Quarks							
Flavor	Symbol	Dressed Mass in GeV (Constituent mass)	Charge	Baryonic Number	Color	Other quantum numbers	Bare Mass in MeV
Up	u	0.31	+2/3	+1/3	r,g,b	--	2
Down	d	0.31	-1/3	+1/3	r,g,b	--	5
Charm	c	1.5	+2/3	+1/3	r,g,b	C = +1	1200
Strange	s	0.5	-1/3	+1/3	r,g,b	S = -1	100
Top	t	180	+2/3	+1/3	r,g,b	T = +1	174000
Bottom	b	4.5	-1/3	+1/3	r,g,b	B = -1	4200
The corresponding antiparticles				-1/3 for all of them	r,g,b	Minus quantum number for antiparticles	

Remarks

- Hadrons are bound states of **constituent (valence) quarks**
- **Bare (current) quarks** are not dressed. We denote the **current quark mass by** m_0
- **Dressed quarks** are surrounded by a cloud of virtual quarks and gluons (**Sea quarks**)
- This cloud explains the large constituent-quark mass M
- For hadrons **the constituent quark mass** M = the binding energy required to make the hadrons spontaneously emit a meson containing the valence quark

For light quarks (u,d,s):	m_0	$\ll$	M
For heavy quarks (c,b,t):	m_0	$\simeq$	M

Remarks:

- **Type of interaction:**
  - All quarks undergo EM and strong interactions
- **Mean lifetime (typical time of interaction):** In general,
  - Particles which mainly decay through strong interactions have a mean lifetime of about 10^{-23} sec
  - Particles which mainly decay through electromagnetic interactions, signaled by the production of photons, have a mean lifetime in the range of $10^{-20} - 10^{-16}$ sec
  - Particles that decay through weak forces have a mean lifetime in the range of $10^{-10} - 10^{-8}$ sec

Other quantum numbers (see Perkins Chapter 4)

Flavor	Baryon B	Spin J	Isospin I	I_3	Charm C	Strangeness S	Topness T	Bottomness B^*	El. Charge Q/e
u	$+1/3$	$1/2$	$1/2$	$+1/2$	0	0	0	0	$+2/3$
d	$+1/3$	$1/2$	$1/2$	$-1/2$	0	0	0	0	$-1/3$
c	$+1/3$	$1/2$	0	0	$+1$	0	0	0	$+2/3$
s	$+1/3$	$1/2$	0	0	0	-1	0	0	$-1/3$
t	$+1/3$	$1/2$	0	0	0	0	$+1$	0	$+2/3$
b	$+1/3$	$1/2$	0	0	0	0	0	-1	$-1/3$

General Formulae for quarks and hadrons

- Baryon number:

$$B = +\frac{1}{3}[(n_u - n_{\bar{u}}) + (n_d - n_{\bar{d}}) + (n_c - n_{\bar{c}}) + (n_s - n_{\bar{s}}) + (n_t - n_{\bar{t}}) + (n_b - n_{\bar{b}})]$$

Charm	C	$=$	$+(n_c - n_{\bar{c}})$
Strangeness	S	$=$	$-(n_s - n_{\bar{s}})$
Topness	T	$=$	$+(n_t - n_{\bar{t}})$
Bottomness	B^*	$=$	$-(n_b - n_{\bar{b}})$

- Hypercharge:

$$Y = B + C + S + T + B^*$$

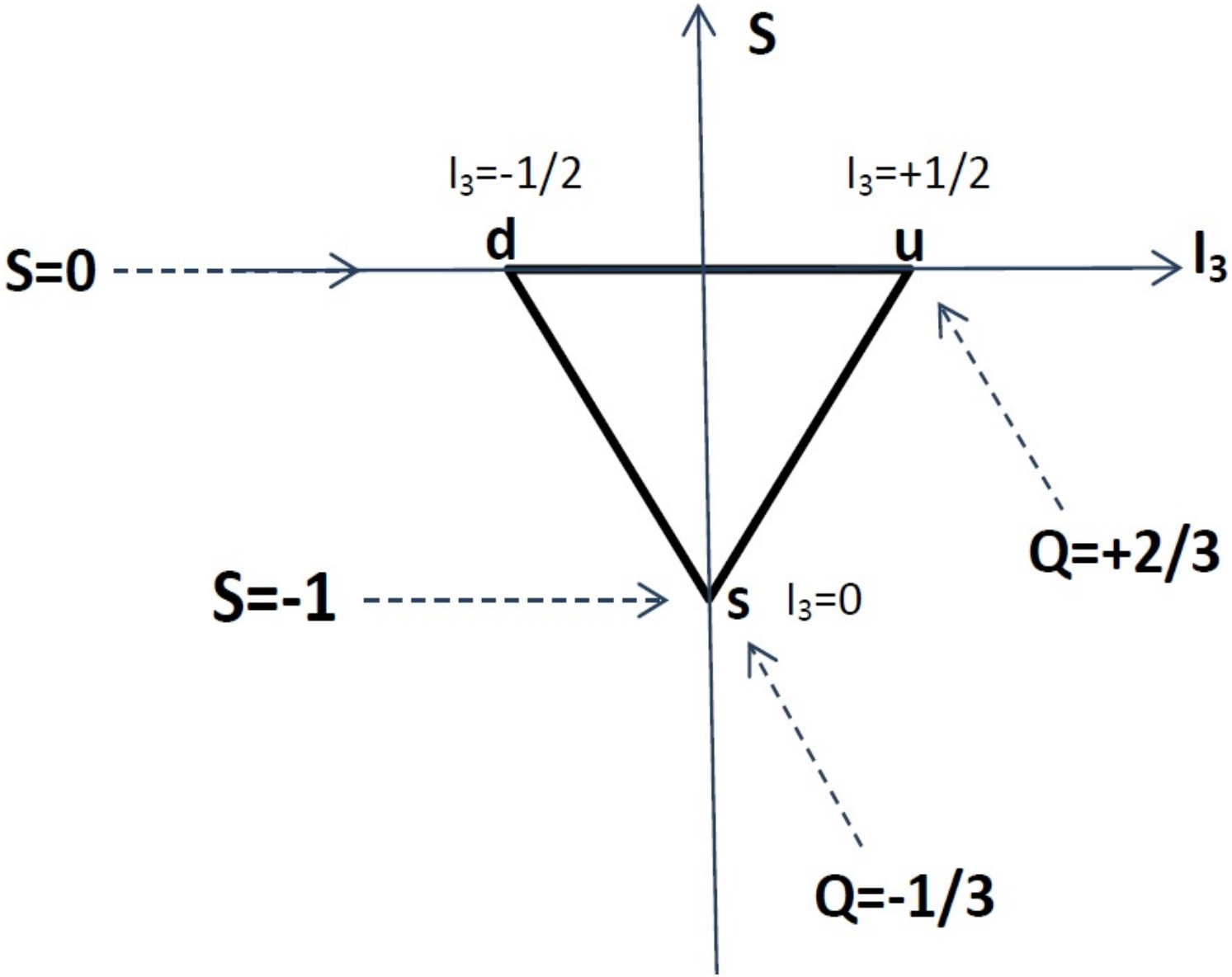
- Electric charge (**Gell-Mann–Nishijima Formula**)

$$\frac{Q}{e} = I_3 + \frac{1}{2}Y$$

Interactions

Conserved quantity	Strong nuclear	Electromagnetic	Weak nuclear
Energy/Momentum	Yes	Yes	Yes
Charge	Yes	Yes	Yes
Baryon number	Yes	Yes	Yes
Lepton number	Yes	Yes	Yes
I (Isospin)	Yes	No	$\Delta I = 1, 1/2$
S (Strangeness)	Yes	Yes	$\Delta S = 0, 1$
C (Charm)	Yes	Yes	$\Delta C = 0, 1$
P (Parity)	Yes	Yes	No
C (C Parity)	Yes	Yes	No
CP (or T)	**Yes**	Yes	No (K^0 decay)
CPT	Yes	Yes	Yes

Quark patterns



Hadrons

Baryons and Mesons

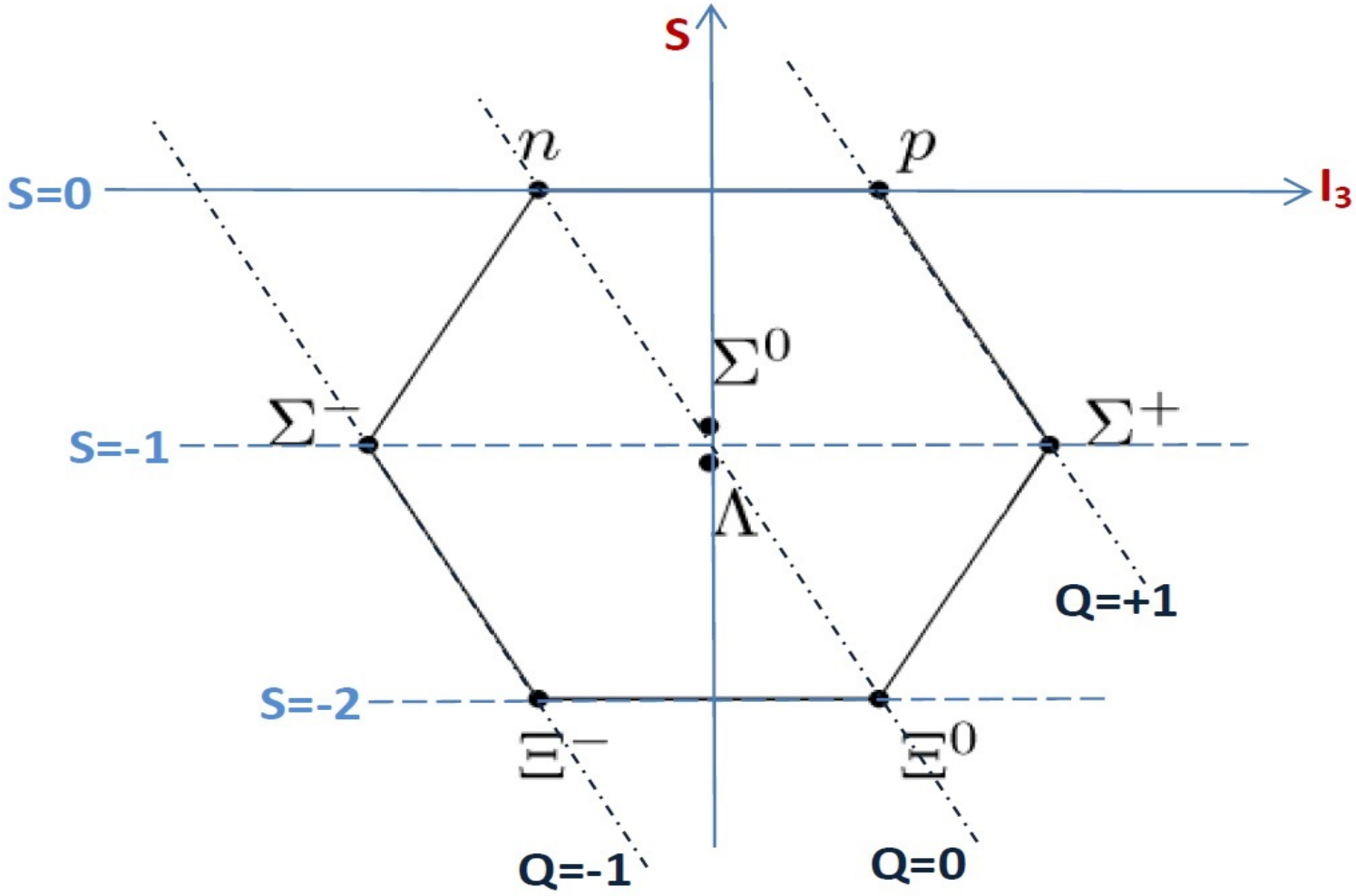
Eightfold way (Baryon Octet), Baryon decuplet

Pseudoscalar and vector mesons

Baryon Octet (u,d,s)

Baryon Octet		Q/e	S	Isospin	I_3	(mean) Mass/MeV	J^P
n	udd	0	0	+1/2	-1/2	N (939) Nucleon Isospindublet	Spin-Parity = $\mathbf{+1/2^+}$ for all members of Baryon-Octet
p	uud	+1	0	+1/2	+1/2		
Σ^-	dds	-1	-1	+1	-1	Σ (1193) Σ Isospintriplet	
Σ^0	uds	0	-1	+1	0		
Σ^+	uus	+1	-1	+1	+1		
Λ	uds	0	-1	0	0	Λ (1116) Isospinsinglet	
Ξ^-	dss	-1	-2	+1/2	-1/2	Ξ (1318) Ξ Isospindublet	
Ξ^0	uss	0	-2	+1/2	+1/2		

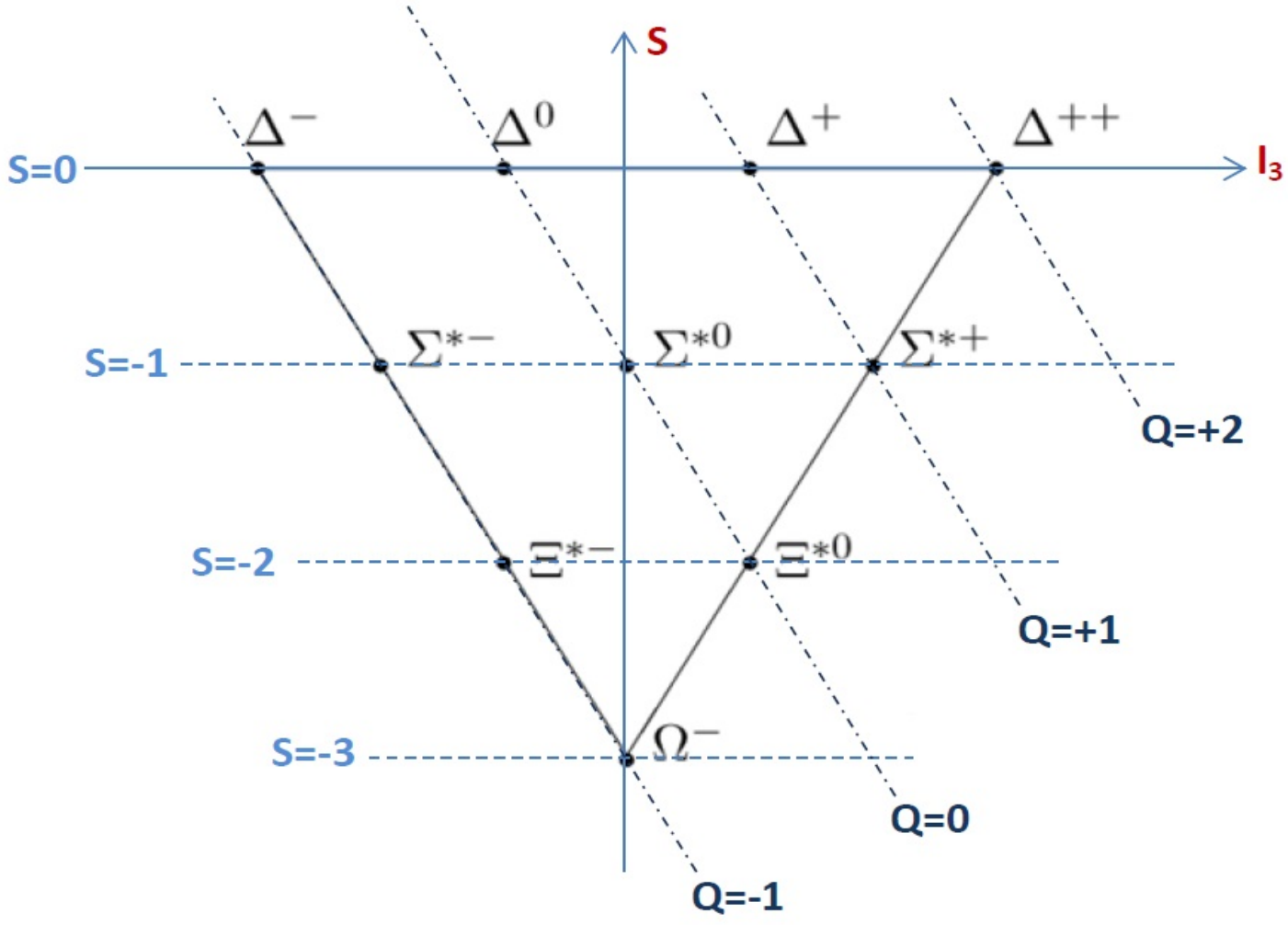
Baryon Octet (u,d,s)



Baryon decuplet (u,d,s)

Baryon Decuplet		Q/e	S	I	I_3	(mean)Mass/MeV	J^P
Δ^-	ddd	-1	0	+3/2	-3/2	Δ (1232) Isospinquadruplet	Spin-parity= $+3/2^+$ for all members of baryon decuplet
Δ^0	ddu	0	0	+3/2	-1/2		
Δ^+	duu	+1	0	+3/2	+1/2		
Δ^{++}	uuu	+2	0	+3/2	+3/2		
Σ^{*-}	dds	-1	-1	+1	-1	Σ (1384) Isospintriplet	
Σ^{*0}	dus	0	-1	+1	0		
Σ^{*+}	uus	+1	-1	+1	+1		
Ξ^{*-}	dss	-1	-2	+1/2	-1/2	Ξ (1533) Isospindublet	
Ξ^{*0}	uss	0	-2	+1/2	+1/2		
Ω^-	sss	-1	-3	0	0	Ω (1672) Isospinsinglet	

Baryon decuplet (u,d,s)



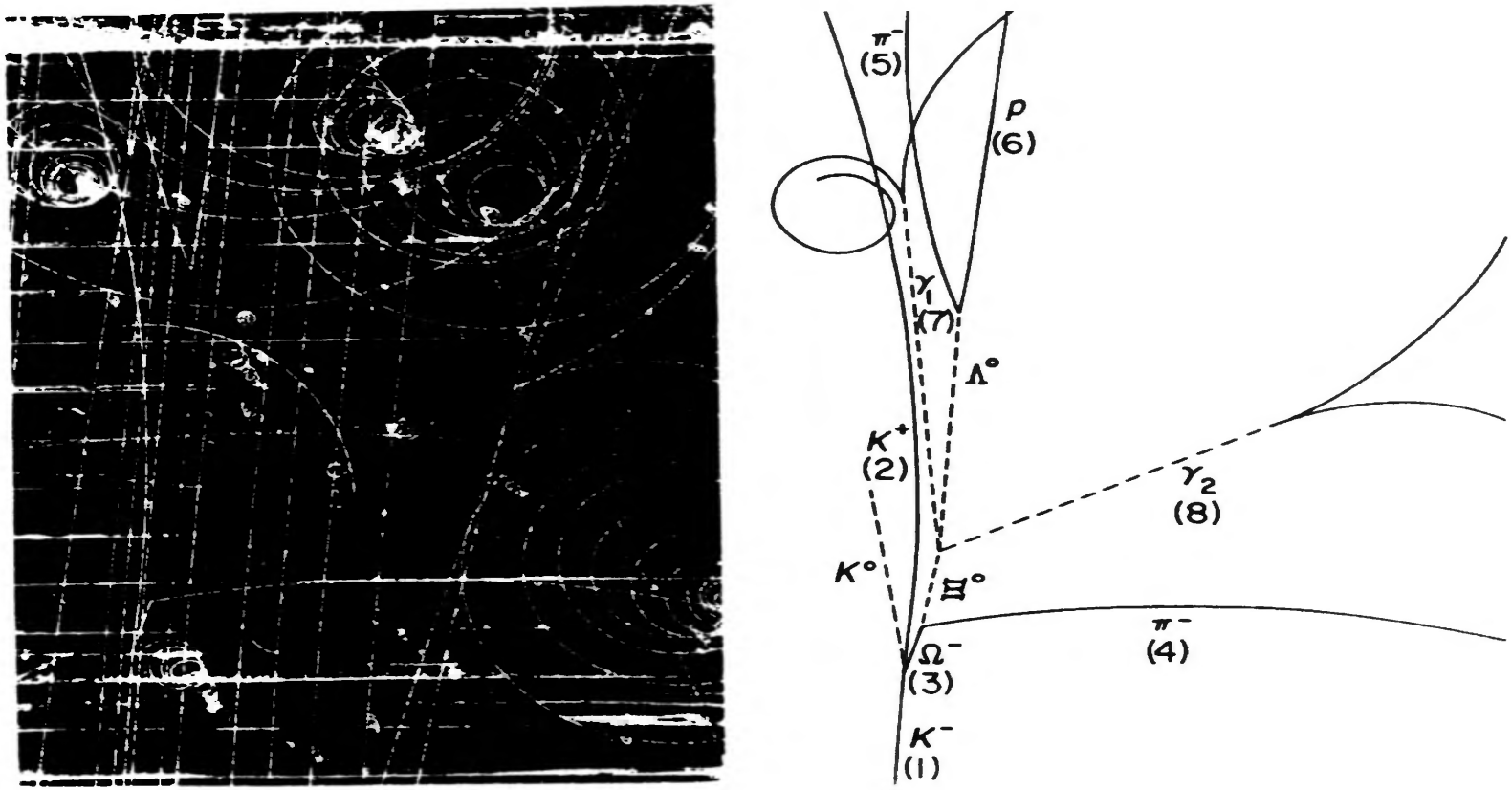
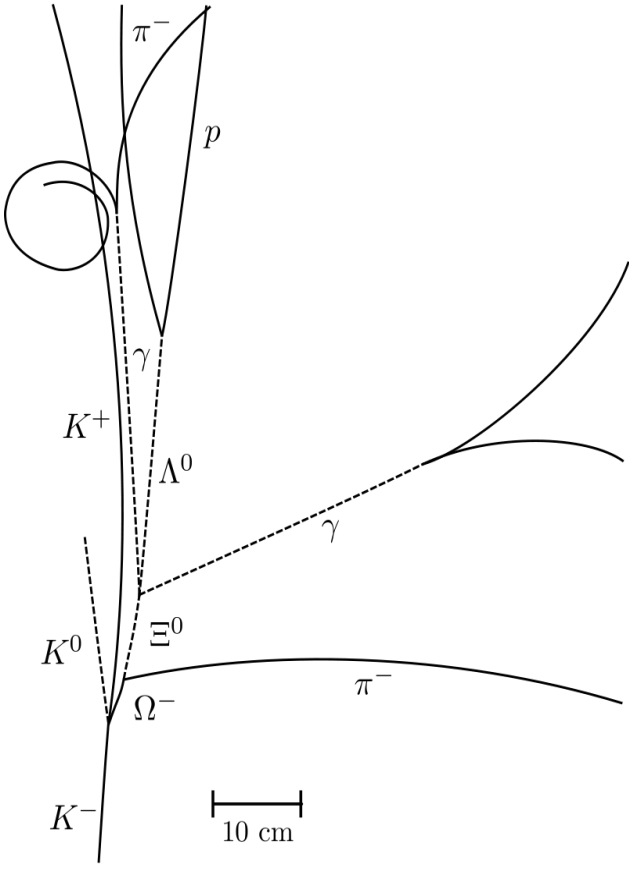


Fig. 4.11. The first Ω^- event (Barnes *et al.* 1964), courtesy Brookhaven National Laboratory). It depicts the following chain of events:

$$K^- + p \rightarrow \Omega^- + K^+ + K^0$$
$$\hookrightarrow \Xi^0 + \pi^- \ (\Delta S = 1 \text{ weak decay})$$
$$\hookrightarrow \pi^0 + \Lambda \ (\Delta S = 1 \text{ weak decay})$$
$$\hookrightarrow \pi^- + p \ (\Delta S = 1 \text{ weak decay})$$
$$\hookrightarrow \gamma + \gamma \text{ (electromagnetic decay)}$$
$$\downarrow \quad \downarrow$$
$$e^+e^- \quad e^+e^-$$

Lecture 10



[1] $\begin{cases} p + K^- & \to & K^0 + K^+ + \Omega^- \\ uud + s\bar{u} & \to & d\bar{s} + u\bar{s} + sss \\ 0 + (-1) & \to & 1 + 1 - 3 \end{cases}$ $\Delta S = 0$ (*Strong*)

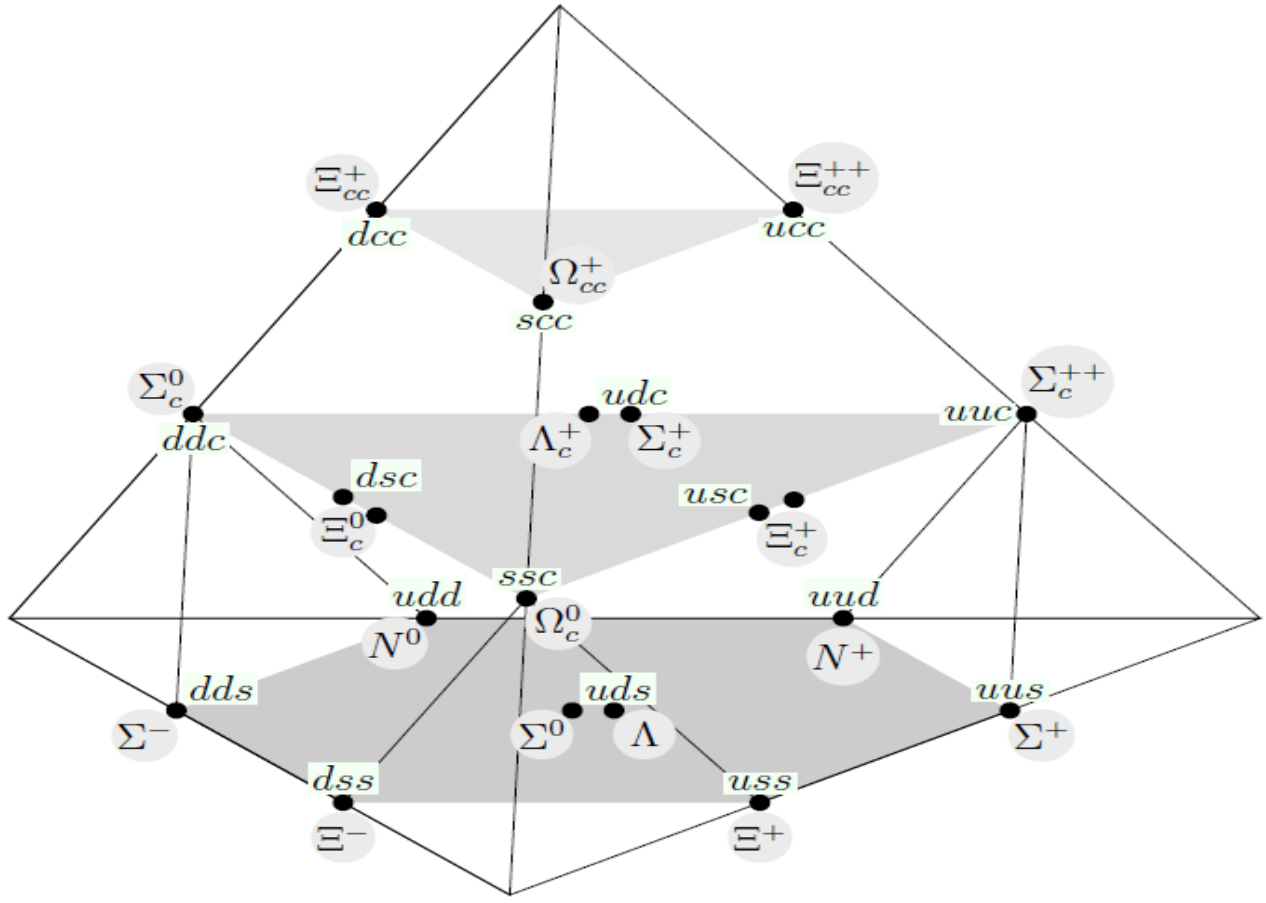
[2] $\begin{cases} \Omega^- & \to & \pi^- + \Xi^0 \\ sss & \to & d\bar{u} + uss \\ -3 & \to & 0 - 2 \end{cases}$ $\Delta S = 1$ (*Weak*)

[3] $\begin{cases} \Xi^0 & \to & \pi^0 + \Lambda^0 \\ uss & \to & u\bar{u} + uds \\ -2 & \to & 0 - 1 \end{cases}$ $\Delta S = 1$ (*Weak*)

[4] $\begin{cases} \Lambda^0 & \to & \pi^- + p \\ uds & \to & d\bar{u} + uud \\ -1 & \to & 0 + 0 \end{cases}$ $\Delta S = 1$ (*Weak*)

[5] $\{ \pi^0 \to 2\gamma \to 2(e^+ + e^-)$ $\Delta S = 0$ (*EM*)

Baryon Multiplet (u,d,s,c)



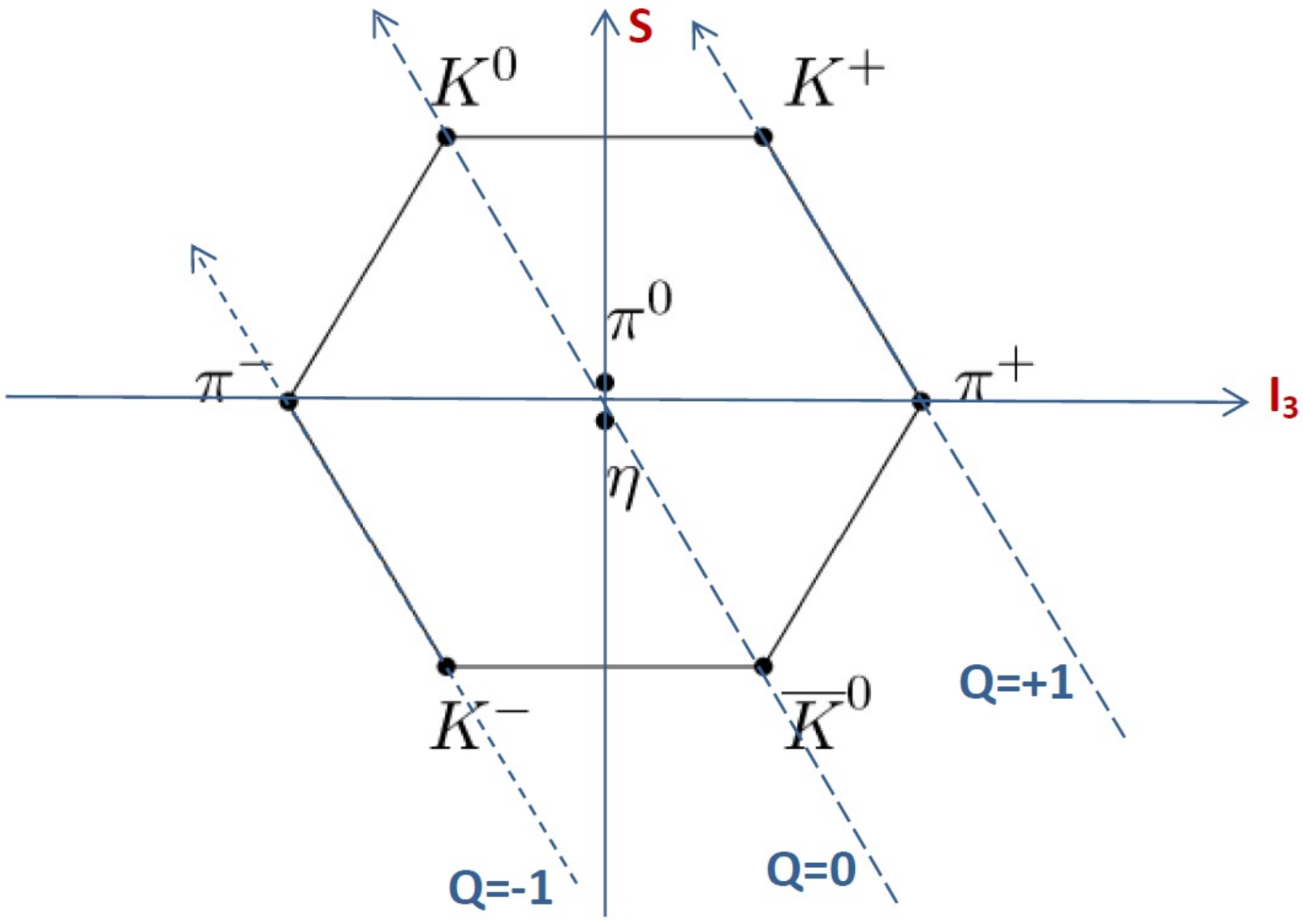
- Antibaryons (opposite charges and quark flavor quantum numbers) are not in the same multiplets as the baryons

Pseudo-scalar Mesons (u,d,s)

Pseudoscalar Mesons			Q/e	S	I	I_3	Mass (MeV)	Decay	J^P
K^0	$d\bar{s}$	Octet	0	+1	+1/2	-1/2	498	$K^0 \rightarrow \pi^+\pi^-$	Spin-Parity= $\mathbf{0^-}$ All pseudoscalar mesons are spin singlet
K^+	$u\bar{s}$		+1	+1	+1/2	+1/2	494	$K^+ \rightarrow \mu^+ \nu_\mu$	
π^-	$d\bar{u}$		-1	0	+1	-1	140	$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$	
π^0	$u\bar{u}$ or $d\bar{d}$		0	0	+1	0	135	$\pi^0 \rightarrow 2\gamma$	
π^+	$u\bar{d}$		+1	0	+1	+1	140	$\pi^+ \rightarrow \mu^+ \nu_\mu$	
K^-	$s\bar{u}$		-1	-1	+1/2	-1/2	494	$K^- \rightarrow \mu^- \bar{\nu}_\mu$	
$\bar{K}^0$	$s\bar{d}$		0	-1	+1/2	+1/2	498	$\bar{K}^0 \rightarrow \pi^+\pi^-$	
η or η_8	$d\bar{d}$, $u\bar{u}$, $s\bar{s}$		0	0	0	0	549	$\eta \rightarrow 2\gamma$	
η' or η_0	$d\bar{d}$, $u\bar{u}$, $s\bar{s}$	Singlet	0	0	0	0	958	$\eta' \rightarrow \eta\pi\pi \rightarrow 2\gamma$	

- Antimesons (opposite charges and quark flavor quantum numbers) are in the same multiplets as the mesons

Pseudo-scalar Mesons (u,d,s)



Vector Mesons (u,d,s)

Vector Mesons		Q/e	S	I	I_3	Mass (MeV)	Decay	J^P
K^{*0}	$d\bar{s}$	0	+1	+1/2	-1/2	892	$K^* \rightarrow K\pi$	Spin-parity= $\mathbf{1}^-$ All vector mesons are spin triplet
K^{*+}	$u\bar{s}$	+1	+1	+1/2	+1/2			
ρ^-	$d\bar{u}$	-1	0	+1	-1	776	$\rho \rightarrow 2\pi$	
ρ^0	$u\bar{u}$ or $d\bar{d}$	0	0	+1	0			
ρ^+	$u\bar{d}$	+1	0	+1	+1			
K^{*-}	$s\bar{u}$	-1	-1	+1/2	-1/2	892	$K^* \rightarrow K\pi$	
$\bar{K}^{*0}$	$s\bar{d}$	0	-1	+1/2	+1/2			
ϕ or $\boldsymbol{\phi_8}$	$d\bar{d}$, $u\bar{u}$, $s\bar{s}$	0	0	0	0	1019	$\omega \rightarrow 3\pi$	
ω or $\boldsymbol{\phi_0}$	$d\bar{d}$, $u\bar{u}$, $s\bar{s}$	0	0	0	0	783	$\phi \rightarrow K\bar{K}$	