Introduction to Particle Physics/Chemistry

6^{th} Winter School on Astroparticle Physics

Mayapuri, Darjeeling

December 2011

Rajarshi Ray

Center for Astroparticle Physics & Space Science

Bose Institute

Kolkata

Content of the Universe- Today

- Dark Energy ~ 73%
- Dark Matter ~ 23%
- Rest of it is whatever we see and know of!!

We see today matter as small as elementary particles to as large as galaxies and cluster of galaxies.

Birth of Particle Chemistry

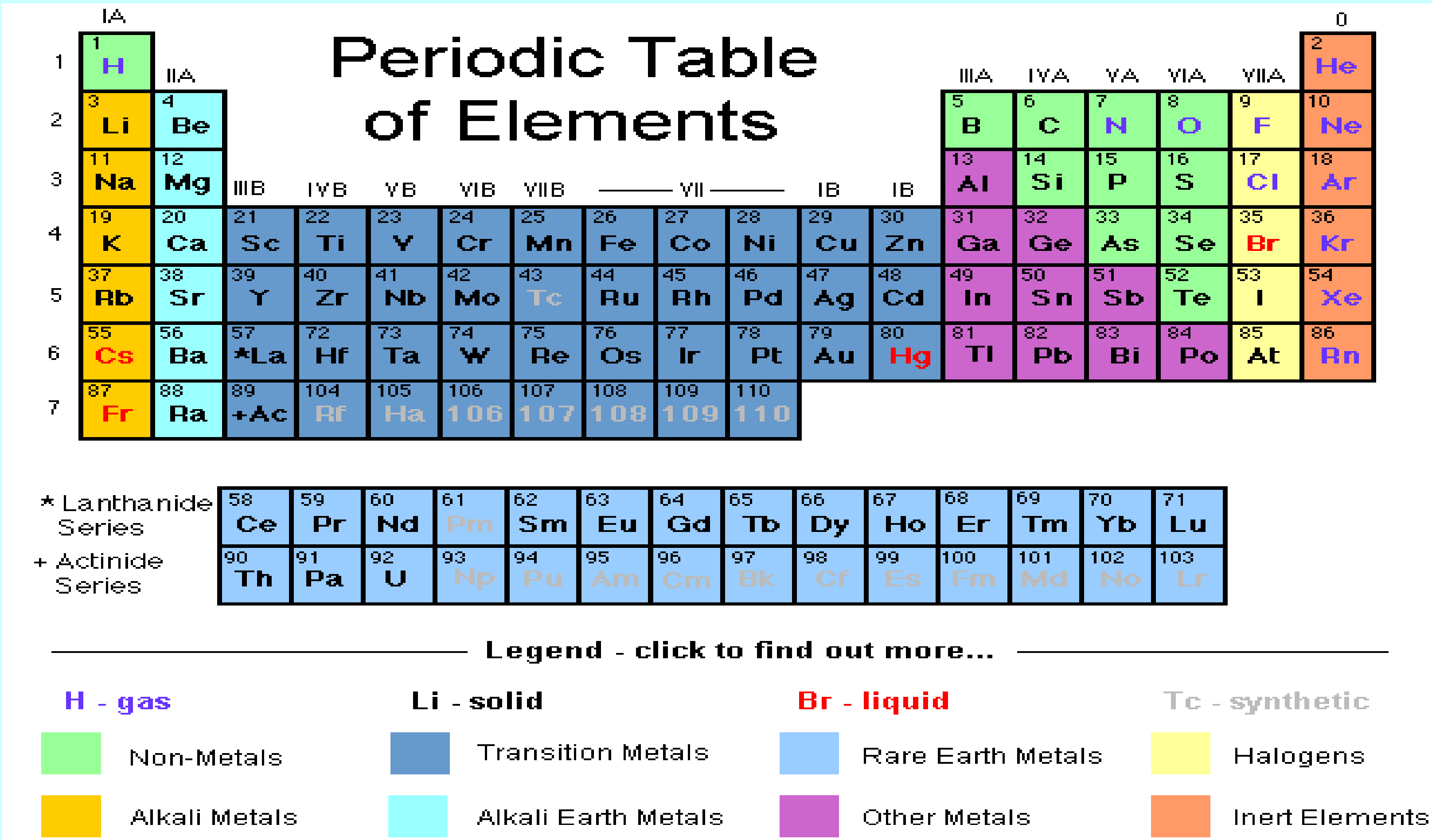
The seeds of Particle physics was sown during the early days of atomic and molecular theories in the context of chemical reactions.

Dalton's atomic theory and Avogadro's hypothesis on number of molecules in a gas provided major advancements in the understanding of particle physics of the early 1800's

Along with this followed the classification of chemical elements from late 1700's to the late 1800's. Significant contributions were made by Lavoisier, Dobereiner, Dumas, Kekule and others.

The modern classification of atomic particles was constructed by Mendeleev and Lothar Meyer.

Particle Physics ~ 1870



Particle chemistry → Particle physics

In 1897 Thomson understood that cathode rays were formed by a train of particles – the electrons. He proposed a plum-pudding model for the atom → atoms are composite particles!!

In 1909 Geiger, Marsden and Rutherford bombarded alpha particles on gold foil and found from the scattered particles that the atoms are almost empty except for very heavy core – the nucleus containing all positive charges of the atom. Electrons are moving around.

- Scattering experiment starts!!
- Nuclear physics starts!!
- Quantum physics about to start!!

In 1913 Bohr proposed a quantum theory of atom to stabilize it against a collapse of the rotating electron on the nucleus by radiation of energy given by the Larmor formula for accelerating charges.

A step ahead – the Nuclear particles

Given the periodic table, slowly the concept of building block of the nucleus started to develop. Through the work of Van den Broeck, Moseley, Rutherford and others, the existence of protons as constituent particles was confirmed (1913 - 1919).

Experiments involved anode rays, X-rays and scattering of α particles.

Thereafter the conflict of atomic mass with the number of protons for various nuclei gave rise to the idea of a neutral particle and through a series of experiments the existence of neutron (1932) by the work of Chadwick and others were developed.

Here again, beryllium etc. were bombarded by α particles, ejecting the neutron.

Models for the nuclear structure started to emerge – Shell Model, Liquid Drop model, etc.

Quantum Mechanics

The quantum nature of light was used by Planck in 1900 to describe the character of black body radiation.

In 1905 Einstein confirmed the quantum nature by explaining the photo-electric effect.

Later in 1923 scattering of X-rays and γ-rays on electrons in atoms was explained again with the quantum nature of light by Compton.

Photons as particles or quantum of the electromagnetic field was established.

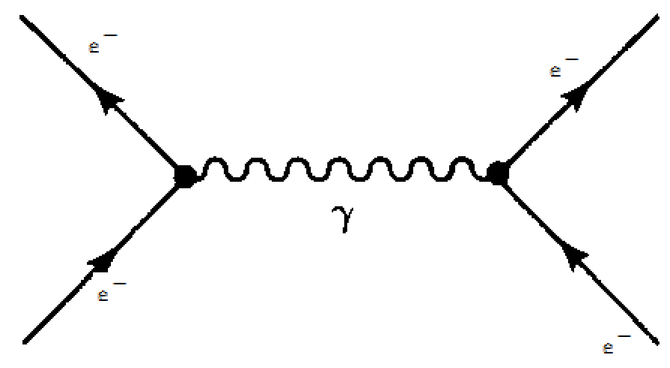
Bose formulated the statistical mechanics of photons around 1924.

Quantum mechanics got itself a prominent place through the work of Plank, Einstein, Heisenberg, Shroedinger, Born, Pauli, Dirac, etc.

Spin and anti-particles

- Pauli – 1924 – suggested additional quantum number for electron in an atom which could take two values
- Goudsmit & Uhlenbeck – 1925 – explained the fine structure in atomic spectra – introduced spin angular momentum for electrons in addition to orbital angular momentum
- Dirac – 1927 - Relativistic equation for electron
  - Natural basis for electron spin
  - existence of antiparticle
- Discovery of positron – 1932 – Anderson – Cosmic Ray

- 1950s – Quantum Electrodynamics (Tomonaga, Feynman, Dyson, Schwinger, etc.)
  - quantization of electromagnetic field $\longrightarrow$ Photon
  - charged particles interact with the exchange of photon



Moller scattering

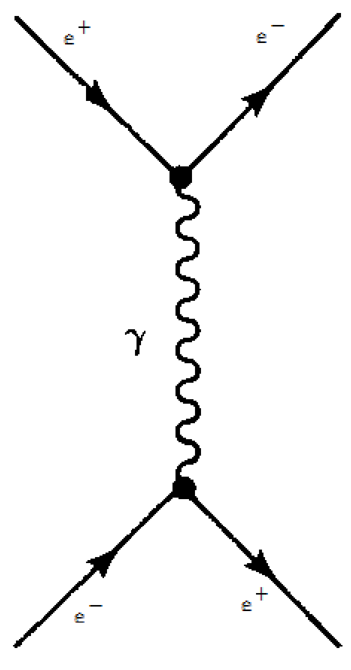
Crossing Symmetry

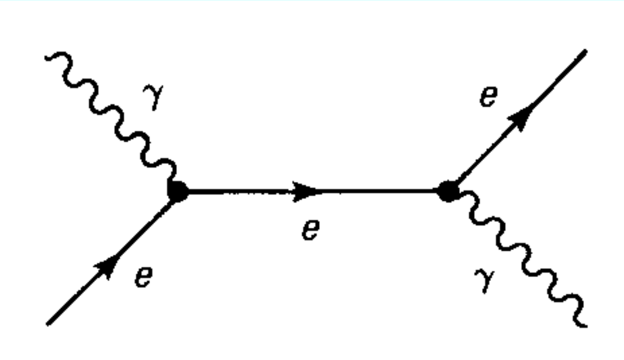
if $A + B \rightarrow C + D$ is allowed

then $A \rightarrow \bar{B} + C + D$

$A + \bar{C} \rightarrow \bar{B} + D$

$\bar{C} + \bar{D} \rightarrow \bar{A} + \bar{B}$ are allowed





Compton scattering

Bhabha scattering

- What binds proton and neutron in the nucleus??
- Positively charged protons should repel each other.
- some force stronger than electromagnetic force

  \- STRONG FORCE
- First evidence – 1921 – Chadwick & Bieler

  α scattering on hydrogen can not be explained by Coulomb interaction only
- Why we do not feel this force everyday?

  \- must be of short range

$$F \sim \frac{e^{-r/a}}{r^n}$$

Gravitational and electromagnetic forces have infinite range; a=∞

For strong a ≈ 10^{-13} cm = 1 fm

Mediator of strong force - pions

- Yukawa -1934

Just as electron is attracted to nucleus by electric field, proton and neutron are also bound by field

- what is the field quanta – pions

- 1939-1942 D.M. Bose and Biva Choudhuri got evidence of such particles right here in this campus from cosmic rays.

- 1947 Independently Powell and co-workers confirmed the exact nature of pions.

- pions are produced copiously in the upper atmosphere but disintegrates before reaching ground

- pion decays into muons which is observed at the ground level

(In your hands on experiments here)

Weak Force

- β decay – If A ⇨ B + e^-

Then for fixed A, the energy of electron will be fixed.

Experimentally, electron energy was found to be varying considerably

Presence of a third particle – the neutrino was proposed by Pauli in 1930 and observed by Reines, Cowan and others around 1956.

Fermi theory of β decay – existence of neutrino

- massless and chargeless

β Decay ➔ $n \rightarrow p + e^- + \bar{\nu}$

π decay ➔ $\pi \rightarrow \mu + \nu$ & $\mu \rightarrow e + 2\nu$

Leptons have $L = +1$
Antileptons have $L = -1$
Everything else has $L = 0$

Lepton Number L is conserved in Strong, EM and Weak interactions but is also separately conserved within lepton families:

e^- and ν_e have $L_e = 1$	e^+ and $\bar{\nu}_e$ have $L_e = -1$
μ^- and ν_μ have $L_\mu = 1$	μ^+ and $\bar{\nu}_\mu$ have $L_\mu = -1$
τ^- and ν_τ have $L_\tau = 1$	τ^+ and $\bar{\nu}_\tau$ have $L_\tau = -1$

L_e, L_μ and L_τ are separately conserved.

✓

	γ	+	N	$\rightarrow$	e^+	+	e^-	+	N
L_e:	0		0		-1		+1		0

Pair Production

✓

	π^+	$\rightarrow$	μ^+	+	ν_μ
L_μ:	0		-1		+1

Pion Decay

✓

	μ^+	$\rightarrow$	e^+	+	ν_e	+	$\bar{\nu}_\mu$
L_e :	0		-1		+1		0
L_μ :	-1		0		0		-1
L :	-1		-1		+1		-1

Muon Decay

✗

	μ^+	$\nrightarrow$	e^+	+	γ	
L_e :	0		-1		0	← Forbidden
L_μ :	-1		0		0	←
L :	-1		-1		0	← OK

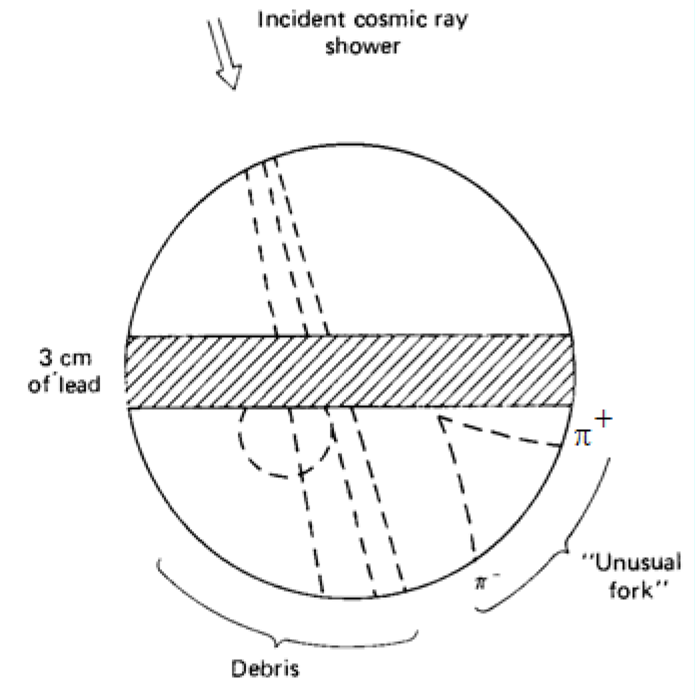
L is conserved but neither L_e or L_μ separately.

The strange particles

1947 – Rochester & Butler – Cosmic ray particle – passing through a lead plate – neutral secondary decaying into two charged particles

$$K^0 \rightarrow \pi^+ + \pi^-$$

1949 - Powell – $K^+ (\tau^+) \rightarrow \pi^+ + \pi^+ + \pi^-$



$K^+ (\theta^+) \rightarrow \pi^+ + \pi^0$

τ - θ puzzle – Parity violation in weak decays

K particles behave as heavy pions

⟶ K mesons (strange meson)

1950 – Anderson – photograph similar to Rochester's

$\Lambda \rightarrow p^+ + \pi^-$

Λ Belongs to which family ???

- proton does not decay to neutron – smaller mass
- Also $p^+ \longrightarrow e^+ + \gamma$ does not occur. WHY???
- 1938 Stuckelberg - **Baryon no. conservation**

Baryons have B = +1
Antibaryons have B = -1
Everything else has B = 0

- **Baryon no. is conserved in electromagnetic, weak and strong interactions**

✓

	π^-	+	p	→	K^0	+	Λ^0
B:	0		+1		0		+1

Strong Interaction

✓

	Λ^0	→	p	+	π^-
B:	+1		+1		0

Weak Interaction

Since the proton is the lightest baryon it cannot decay if B is conserved e.g:

✗

	p	$\not\rightarrow$	e^+	+	π^0
B:	+1		0		0

So Λ belongs to baryon family – strange baryon

- Strange particles
- **Gell-Mann & Nishijima** – Strangeness (S) - new Quantum number like lepton no., baryon no. etc
- **Strangeness is conserved in EM and Strong interactions but not in weak interactions**

Strangeness not conserved

- Weak decay

$$\Lambda \longrightarrow p^{+} + \pi^{-}$$
$$\Sigma^{+} \longrightarrow p^{+} + \pi^{0}$$
$$\longrightarrow n + \pi^{+}$$

K meson – S=+1

Λ and Σ - S= -1

Strangeness – conserved

- Strong production

$$\pi^{-} + p^{+} \longrightarrow K^{+} + \Sigma^{-}$$
$$\longrightarrow K^{0} + \Sigma^{0}$$
$$\longrightarrow K^{0} + \Lambda$$

$$\pi^{-} + p^{+} \not\rightarrow \pi^{+} + \Sigma^{-}$$
$$\not\rightarrow \pi^{0} + \Lambda$$
$$\not\rightarrow K^{0} + n$$

Isospin

- After correcting for the electromagnetic interaction, the forces between nucleons (pp, nn, or np) in the same state are almost the same.
- Equality between the pp and nn forces:
- **Charge symmetry.**
- Equality between pp/nnforce and np force:
- **Charge independence.**
- **Better notation: Isospin symmetry;**
- Strong interaction does not distinguish between n and p ⇨ isospin conserved in strong interaction
- BUT not in electromagnetic interaction

Conserved quantum numbers

Quantity		Strong	EM	Weak
Charge	Q	✓	✓	✓
Baryon Number	B	✓	✓	✓
Lepton Number	L	✓	✓	✓
Isospin	I	✓	✗	✗
	I_3	✓	✓	✗
Strangeness	S	✓	✓	✗
Parity	P	✓	✓	✗
Charge Conjugation	C	✓	✓	✗

Zoo is crowded

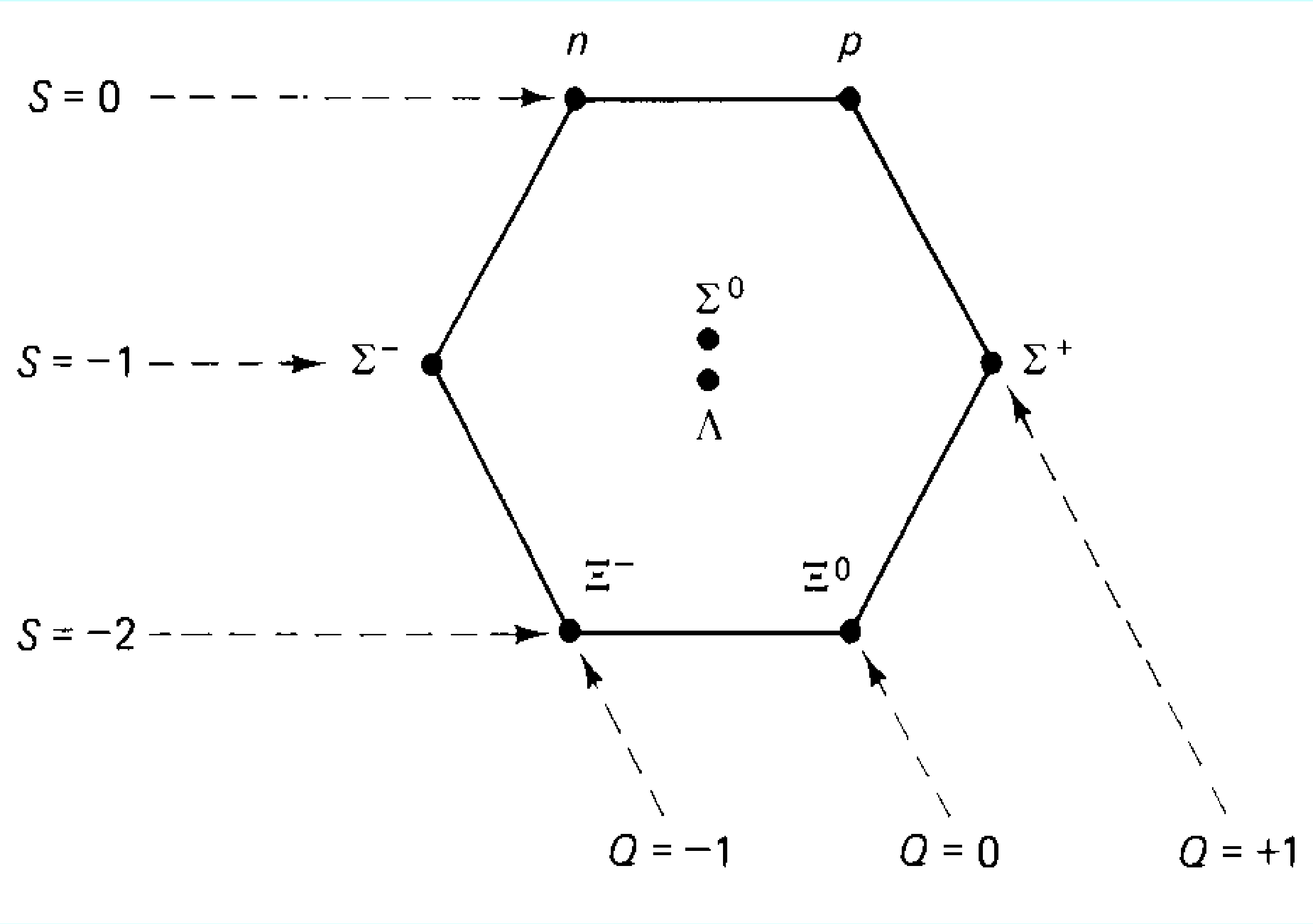
Too many inmates

order required

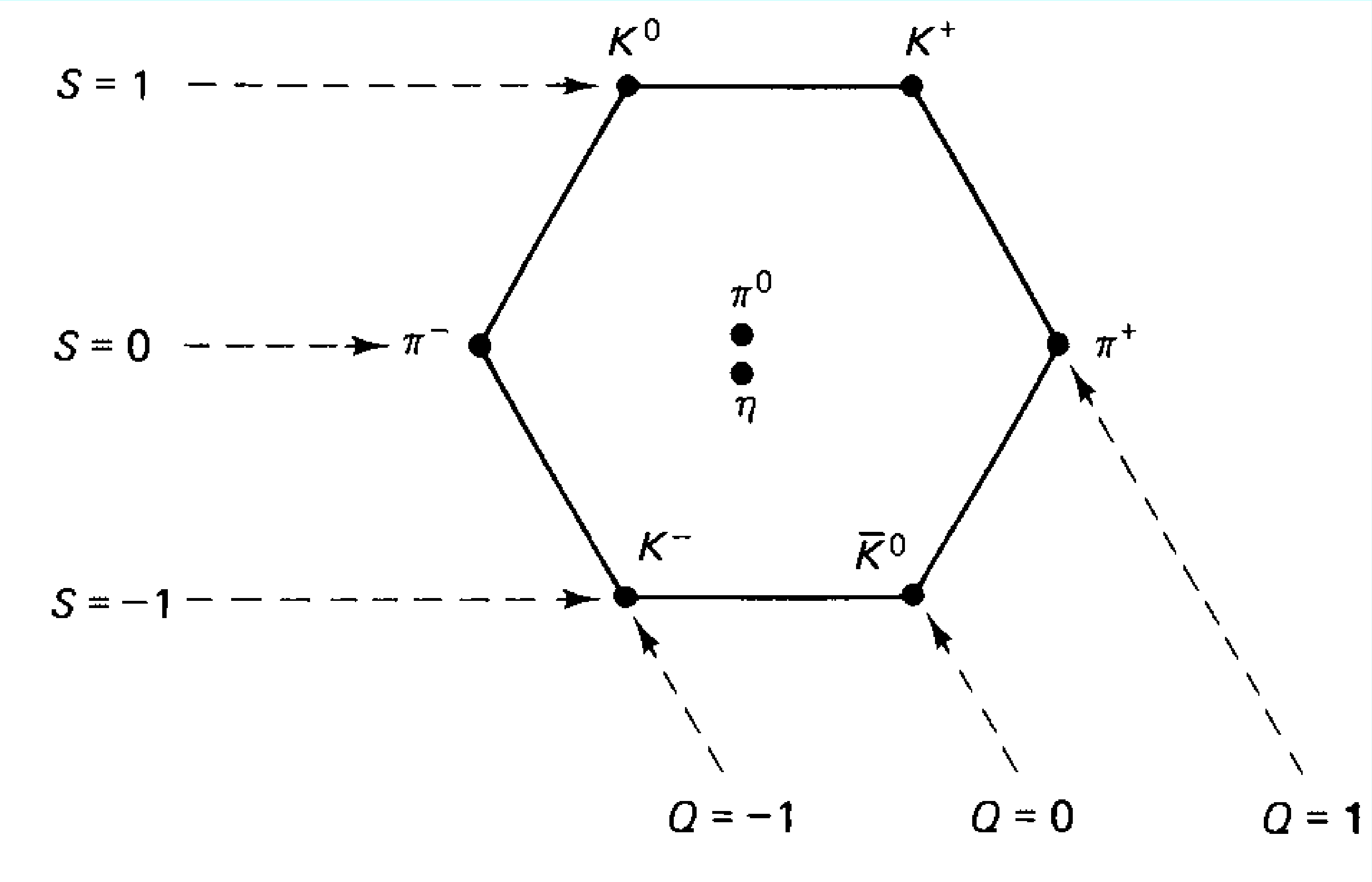
Periodic Table ~ 1960

The "Eightfold Way"

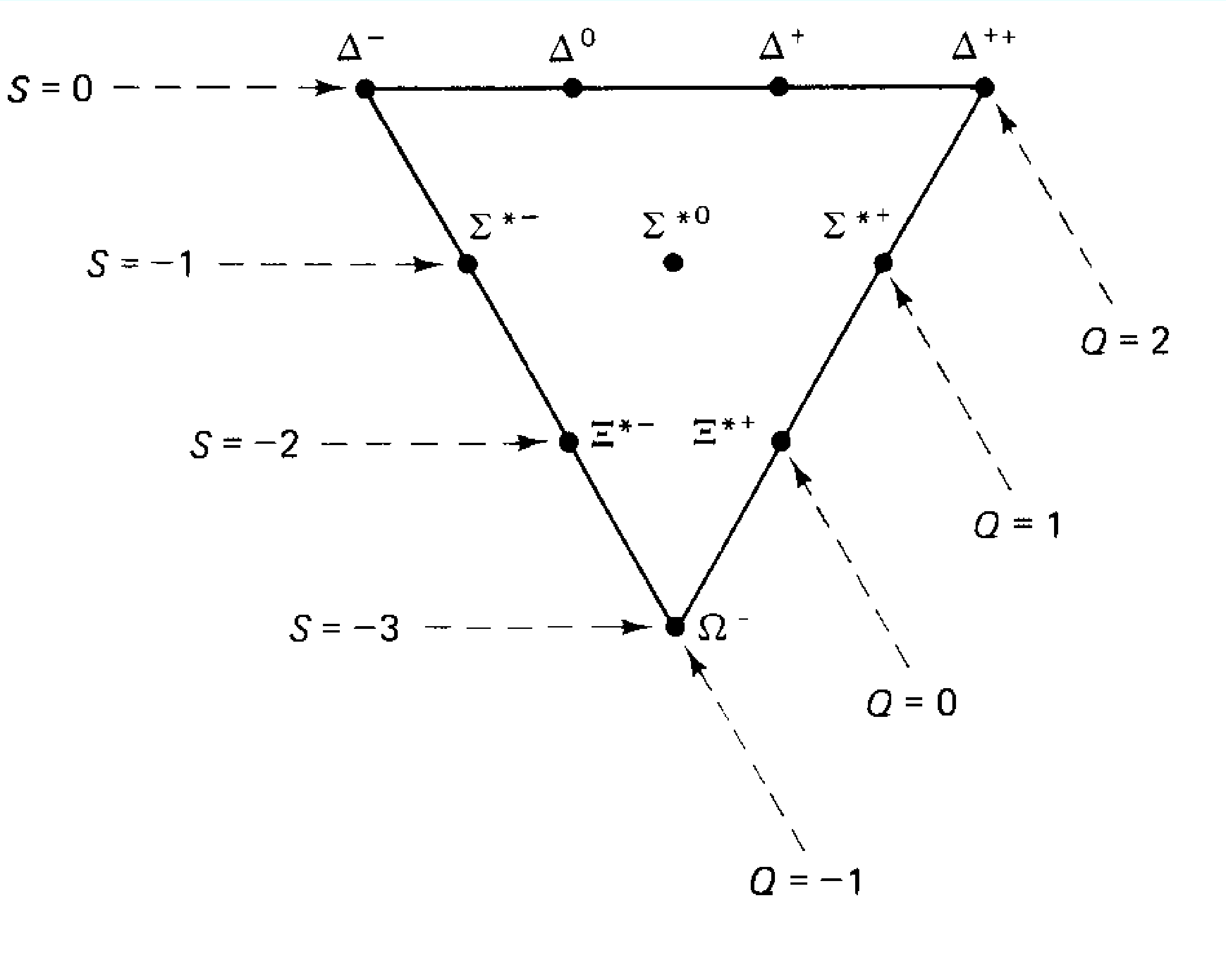
- Murray Gell-Mann and Yuval Ne'eman, 1961



Baryon octet



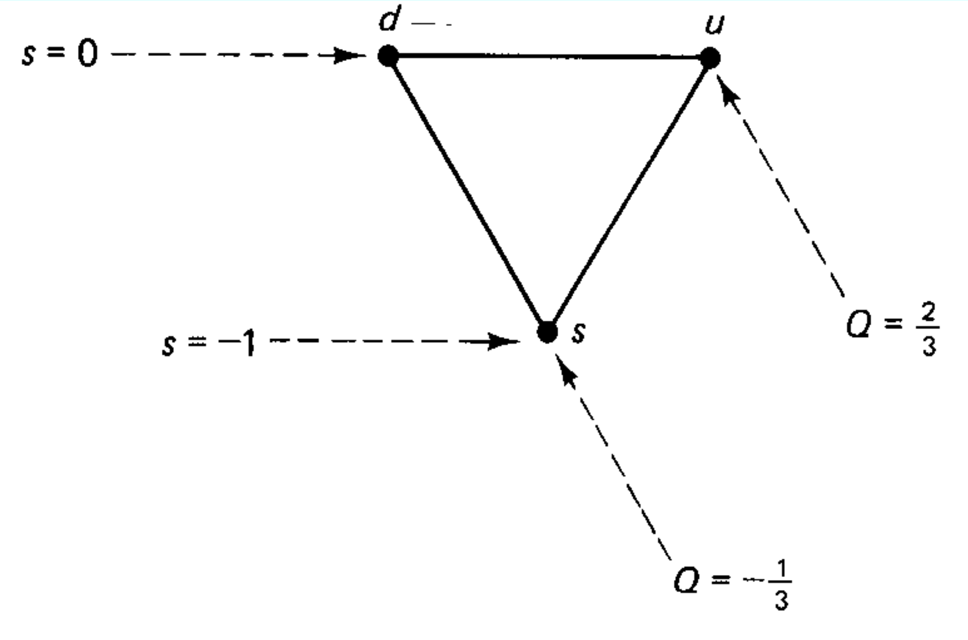
Meson Octet

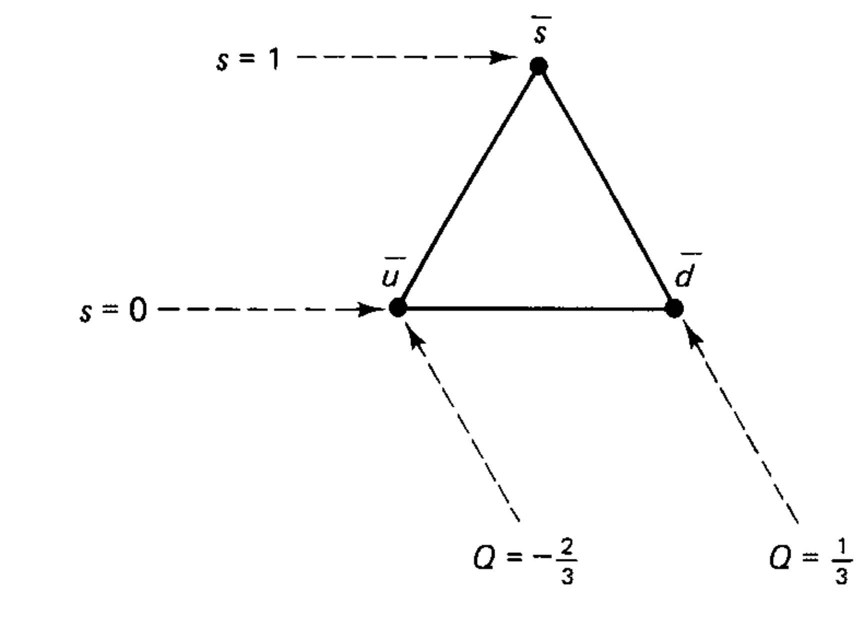


Baryon decuplet

Ω^- was predicted based on this arrangement and was discovered in 1964.

- Why do the hadrons (baryons and mesons) fit so beautifully????
- **Gell-Mann & Zewig proposed independently (1964)**
- Hadrons are composed of spin ½ **QUARKS – comes in three types or** **flavours**

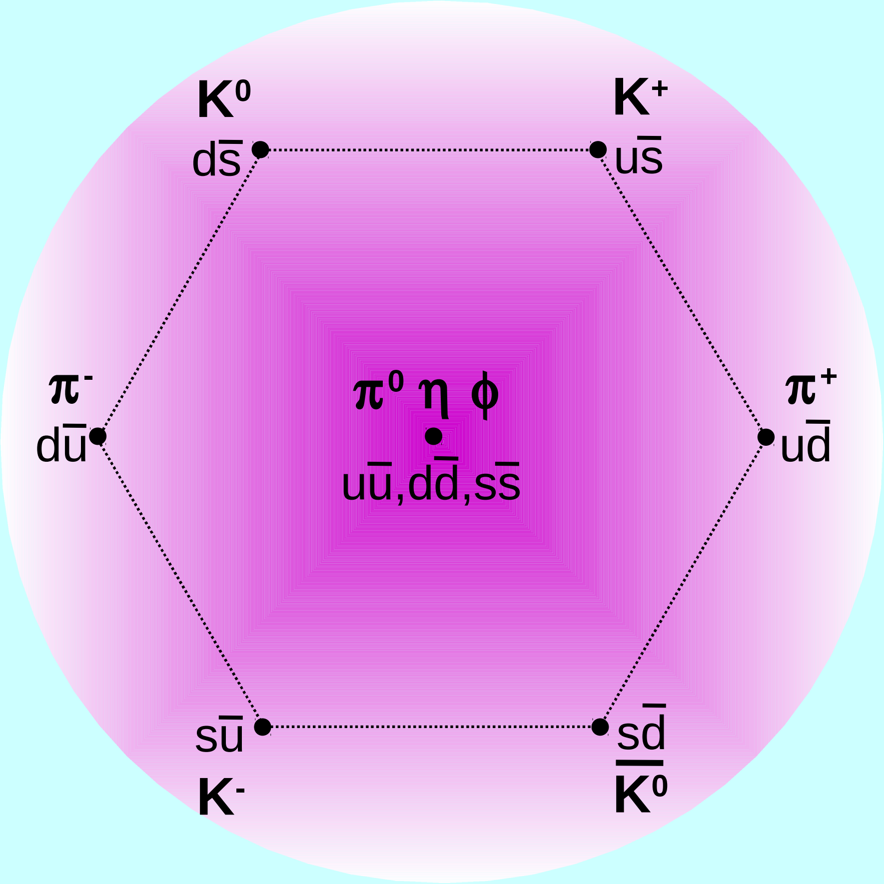




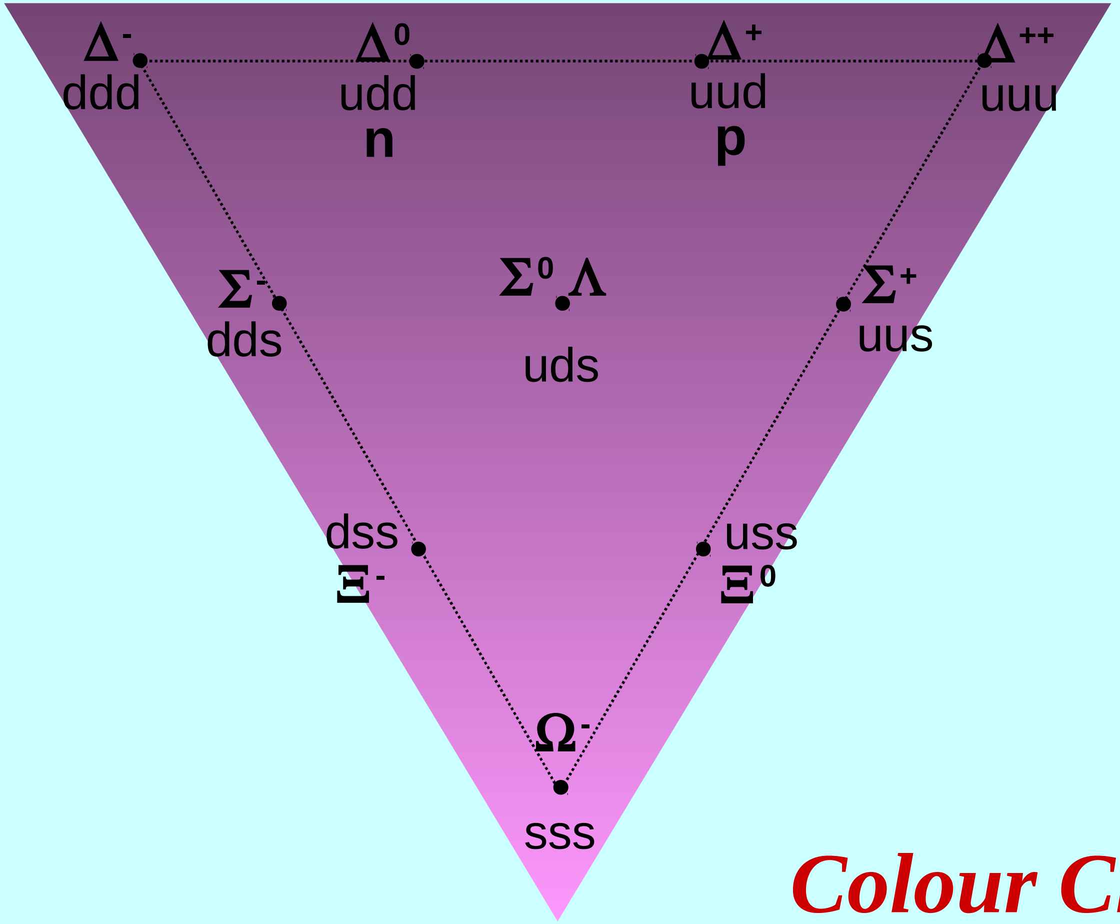
Every baryon (antibaryon) consist of 3 quarks (antiquark) and each meson is composed of a quark and an antiquark

Quark	Up	Down	Strange
Charge	+2/3	-1/3	-1/3

Mesons
$q\bar{q}$



Baryons (qqq) Decuplet



Conceptual problem?

How can we have uuu,ddd or sss state ???

Need for a new quantum number

Colour Charge

Proposed by O. W.Greenberg

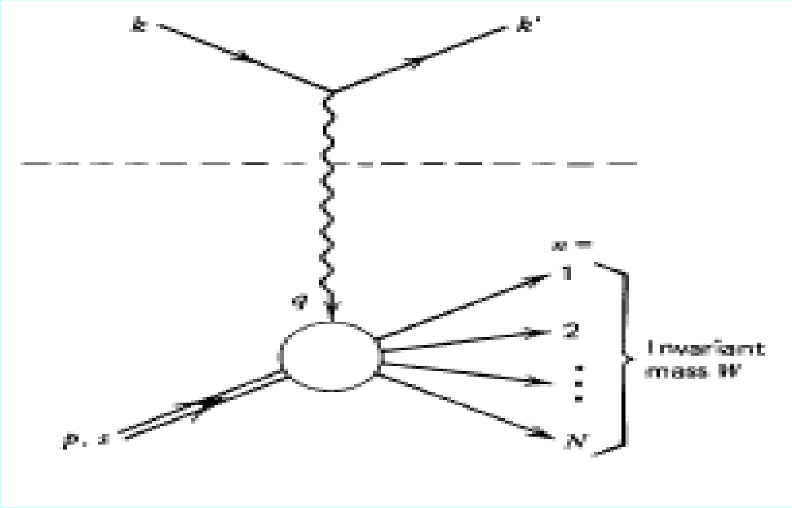
All naturally occurring particles are colourless

Existence of quarks – experimental evidence

- **e-p scattering**
- For smaller energy transfer the scattering is elastic
- For moderate energy transfer proton gets excited

$$e\ p \rightarrow e\ \Delta^{+} \rightarrow e\ p\ \pi^{0}$$

For Higher energies : Deep inelastic Scattering



Can One estimate the energy

Needed to probe proton???

Dimension –

Atom 10^{-10} m

proton – 1fm = 10^{-15}m

Now use Uncertainty principle

- New Theory

Electrons – electric charge - EM force – Photon

Quantum Electrodynamics

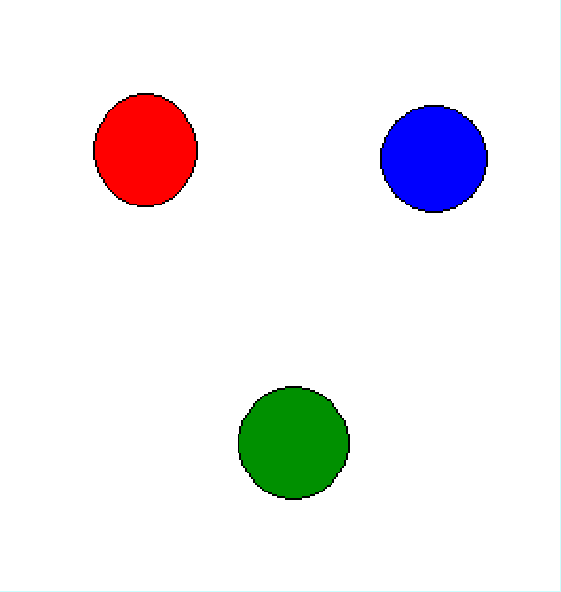
Quarks - Colour Charge - Strong force – Gluon

Quantum Chromodynamics

Quark – three colours - Red , Blue , Green

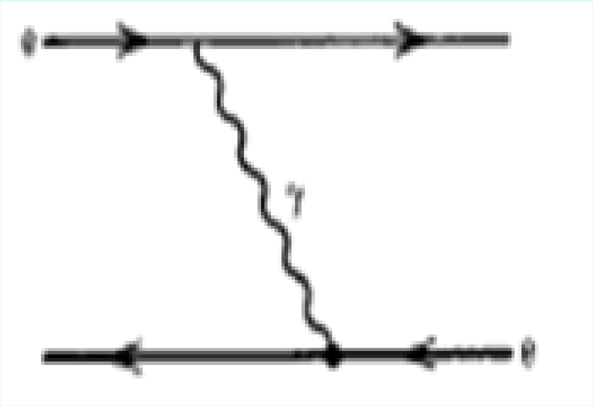
Gluons – eight - red + anti-blue and other combinations

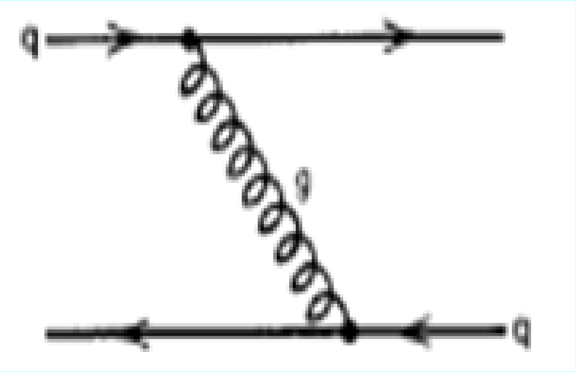
Mesons – quark+antiquark – colour+anticolour – WHITE



Photons – No self Interaction

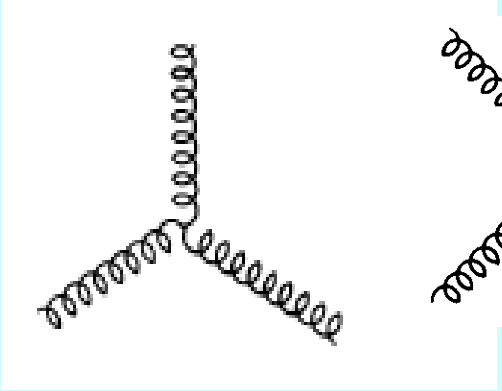
- Abelian theory (QED)
- interaction increases with decreasing separation between particles

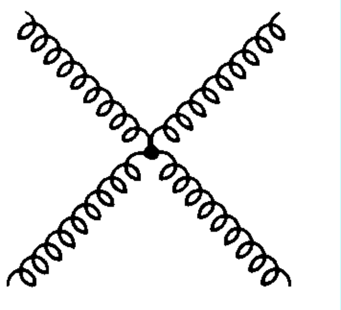


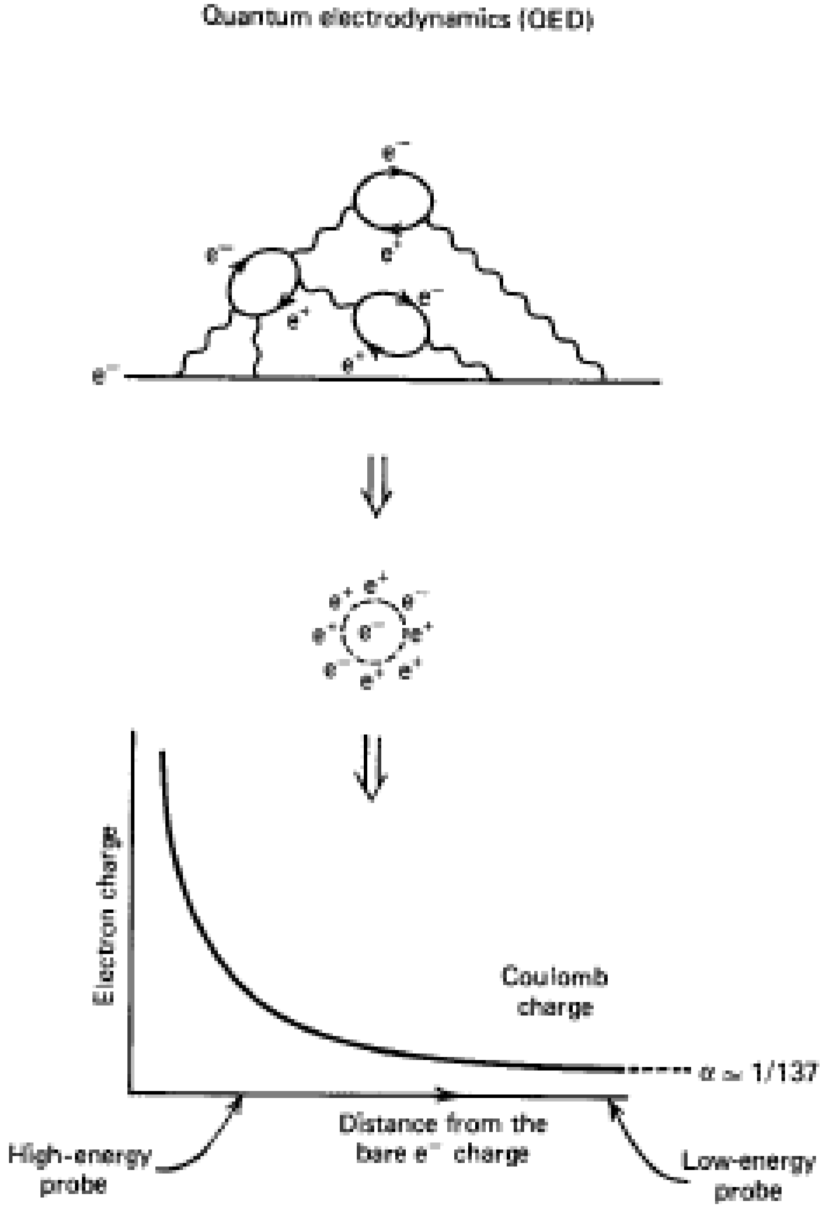


Gluons – colour charge

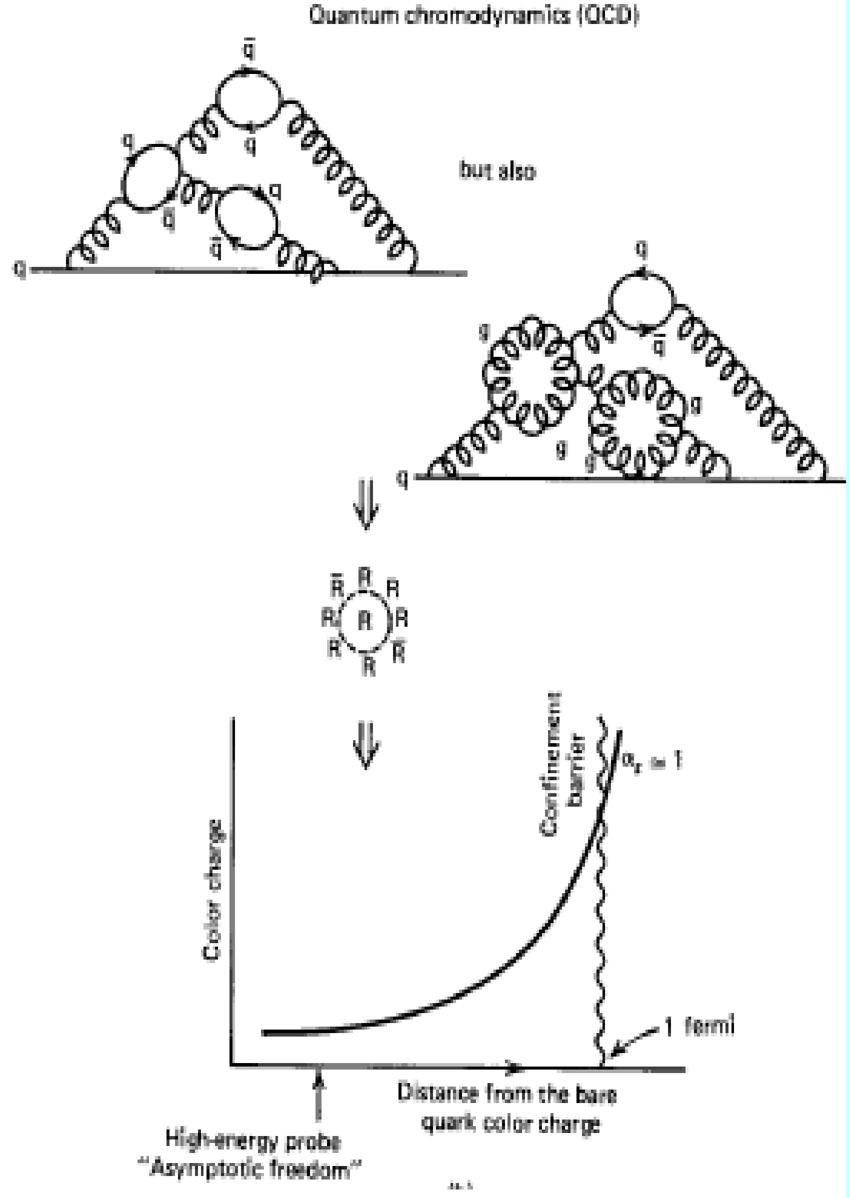
- Self interacting
- Non-abelian theory (QCD)
- interaction decreases with decreasing separation between particles i.e quarks



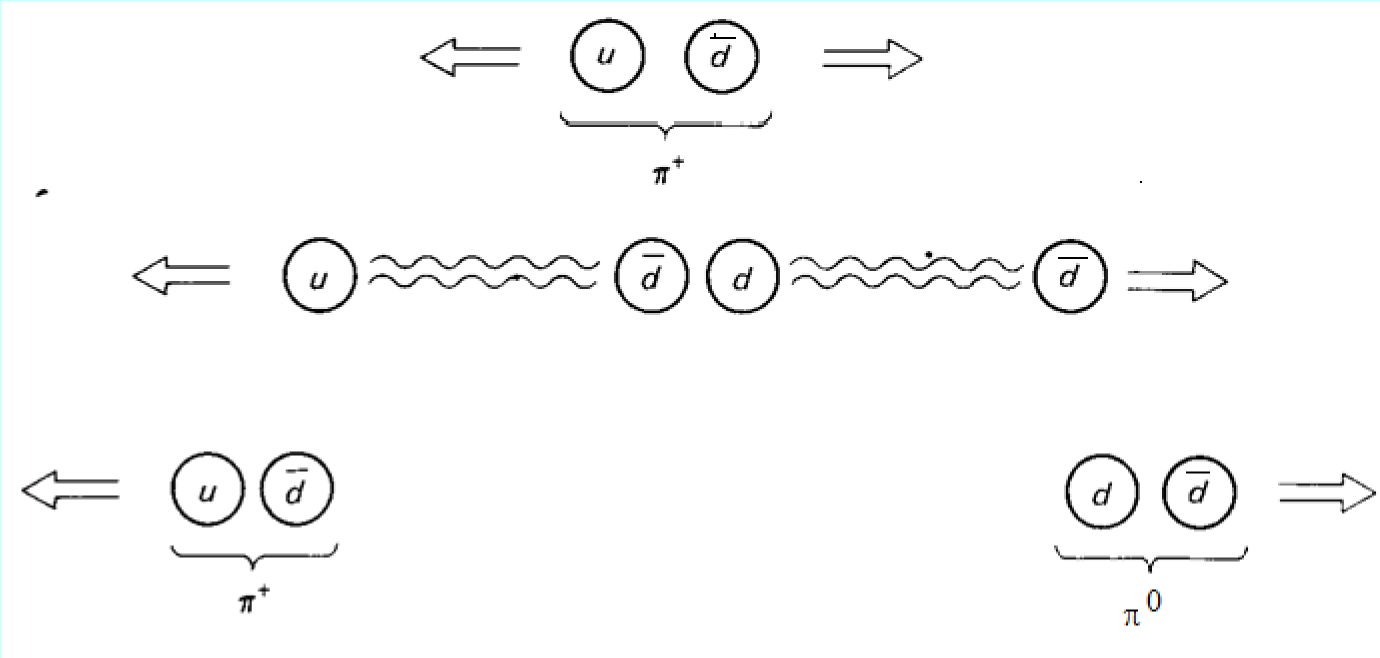


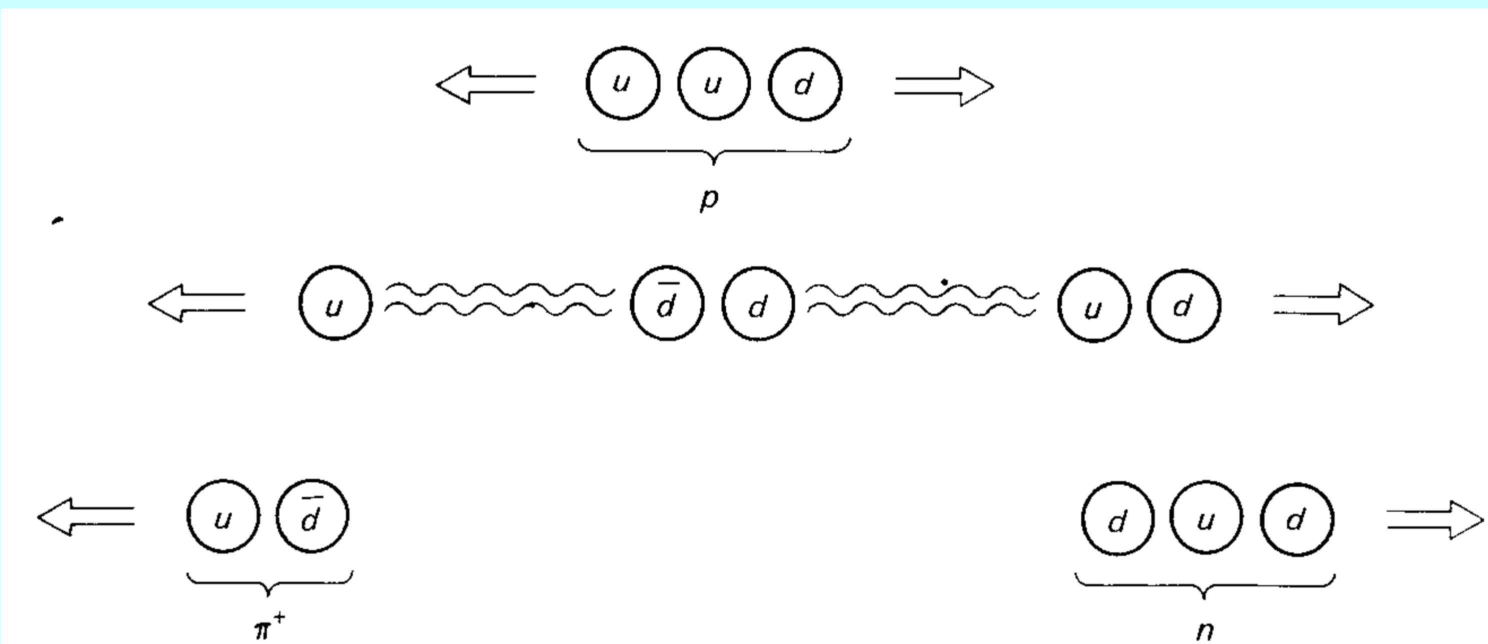


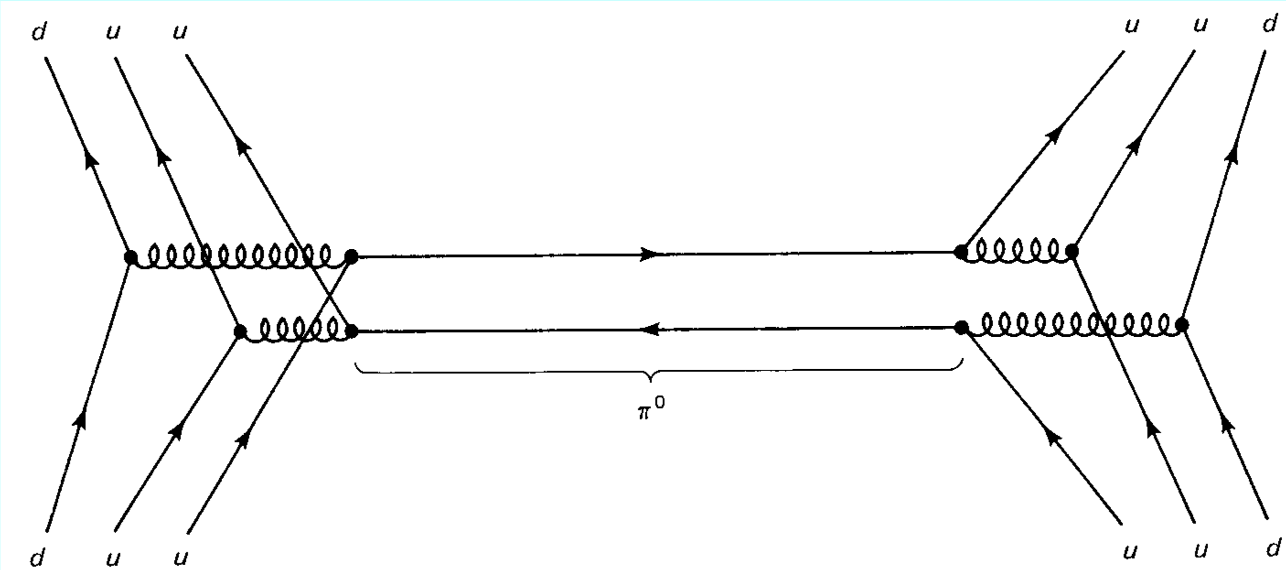
Quantum electrodynamics (QED)
Electron charge
Coulomb charge
$\alpha \simeq 1/137$
Distance from the bare e^- charge
High-energy probe
Low-energy probe



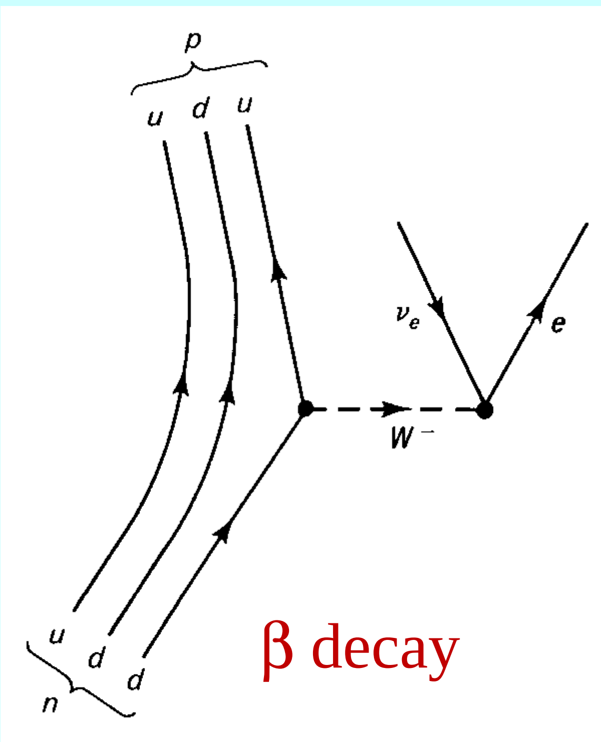
Quantum chromodynamics (QCD)
but also
Confinement barrier
$\alpha_s \simeq 1$
Color charge
1 fermi
Distance from the bare quark color charge
High-energy probe "Asymptotic freedom"


u d̄
π+
u d̄ d d̄
u d̄
π+
d d̄
π0

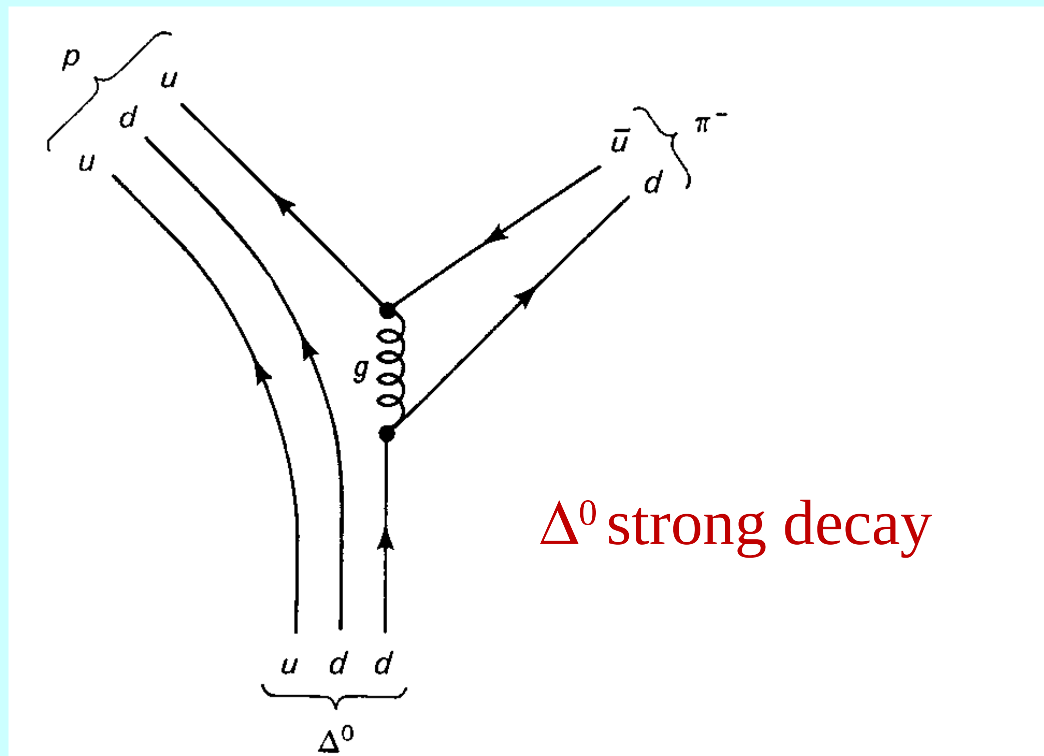

u u d
p
u d̄ d u d
u d̄
π+
d u d
n



Strong force between protons



β decay



Δ^0 strong decay

Story of quarks continues ….

- Quark family does not end with u,d and s as lepton family does not end with e, ν_e , μ, ν_μ

- Bjorken and Glashow – fourth flavour of quark charm c

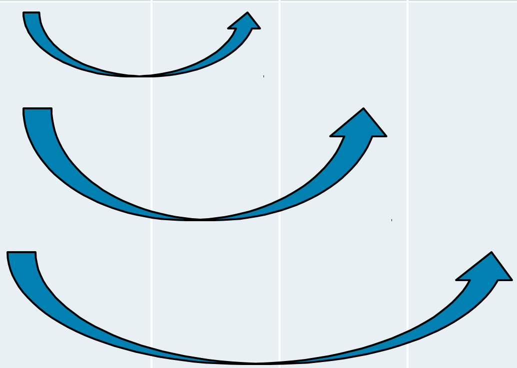
- $c\bar{c}$ meson (called J/ψ) was discovered in 1974

- In 1975 came the tau (τ) lepton and it continued.

- Inclusion of strangeness

  Gell-mann-Nishijima-Nakano relation → $$Q = I_3 + \frac{B+S}{2} = I_3 + \frac{Y}{2}$$

  Hypercharge $Y = B + S$

Flavour	**u**	**d**	**s**	**c**	**t**	**b**
Charge	2/3	-1/3	-1/3	2/3	2/3	-1/3
I_3	1/2	-1/2	0	0	0	0
Strangeness	0	0	-1	0	0	0
Charm	0	0	0	1	0	0
Top	0	0	0	0	1	0
Bottom	0	0	0	0	0	-1
Baryon No.	1/3	1/3	1/3	1/3	1/3	1/3
SU(2)						

For Baryons

B=1

If for any Baryon

$Y \neq 1 \Rightarrow$ Hyperon

Periodic Table - Today

Leptons are colourless

LEPTON CLASSIFICATION

	l	Q	L_e	L_μ	L_τ
First generation	e	-1	1	0	0
	ν_e	0	1	0	0
Second generation	μ	-1	0	1	0
	ν_μ	0	0	1	0
Third generation	τ	-1	0	0	1
	ν_τ	0	0	0	1

All quarks come in three colours

QUARK CLASSIFICATION

	q	Q	D	U	S	C	B	T
First generation	d	$-\frac{1}{3}$	−1	0	0	0	0	0
	u	$\frac{2}{3}$	0	1	0	0	0	0
Second generation	s	$-\frac{1}{3}$	0	0	−1	0	0	0
	c	$\frac{2}{3}$	0	0	0	1	0	0
Third generation	b	$-\frac{1}{3}$	0	0	0	0	−1	0
	t	$\frac{2}{3}$	0	0	0	0	0	1

Mediating particles (radiation)

The weak and electromagnetic interactions were unified by Glashow, Salam and Weinberg

-predicted W and Z bosons with masses 80 GeV and 91 GeV

-Discovered in 1983

Interaction	Strong	EM	Weak
Carrier	g	γ	$W^{\pm} \& Z^0$
Gauge Group	$SU(3)$	$U(1)$	$SU(2)$

Together we have Standard Model of particle physics

Noether's Theorem

Any continuous symmetry transformation implies a conservation law (1915)

- Translational symmetry => conservation of linear momentum
- Rotational symmetry => conservation of angular momentum
- Temporal symmetry => conservation of energy

meroehT s’rehteoN

Any conservation law implies a symmetry transformation

- Electric charge conservation => U(1)
- Weak charge conservation => SU(2)
- Strong charge conservation => SU(3)

Electric charge conservation

The electrons/protons are Fermions and obey Dirac equations

$$\bar{\psi}(\mathrm{i}\gamma^{\mu}\overleftarrow{\partial}_{\mu} + m) = 0 \qquad (\mathrm{i}\gamma^{\mu}\partial_{\mu} - m)\psi = 0.$$

The electric current density is conserved

$$j^{\mu} = \bar{\psi}\gamma^{\mu}\psi$$

$$\partial_{\mu}j^{\mu} = (\partial_{\mu}\bar{\psi})\gamma^{\mu}\psi + \bar{\psi}\gamma^{\mu}(\partial_{\mu}\psi)$$
$$= (\mathrm{i}m\bar{\psi})\psi + \bar{\psi}(-\mathrm{i}m\psi) = 0.$$

Integrating over the entire volume and using Gauss's divergence theorem one finds that the electric charge is conserved

$$Q \equiv \int_{\text{all space}} j^0\, d^3x \qquad j^0 = \bar{\psi}\gamma^0\psi$$

$$\mathrm{d}Q/\mathrm{d}t = 0.$$

Electric charge conservation

Let us consider the transformed fermions

$$\psi(x) \to e^{i\alpha}\psi(x)$$

For constant α these also satisfy the same Dirac equations

$$\bar{\psi}(\mathrm{i}\gamma^{\mu}\overleftarrow{\partial}_{\mu} + m) = 0 \qquad (\mathrm{i}\gamma^{\mu}\partial_{\mu} - m)\psi = 0.$$

and hence satisfy the electric charge conservation

$$Q \equiv \int_{\text{all space}} j^0 \, d^3x \qquad j^0 = \bar{\psi}\gamma^0\psi$$

$$\mathrm{d}Q/\mathrm{d}t = 0.$$

Thus we see that under an U(1) symmetry transformation the electric charge is conserved….. BUT !!!

Electric charge conservation

…... Electric force acts at a distance !!!

Gauge Principle: (Salam and Ward ~ 1961)
All action-at-a-distance forces arise out of local symmetries

$$\psi \to \psi' = \exp\left[-i\alpha(x)\right]\psi$$

The Dirac equation doesn't remain invariant
Neither does the current conservation hold

- Change the Dirac equation!!!

Use $D_\mu \equiv \partial_\mu + ieA_\mu$ along with $A_\mu \to A'_\mu = A_\mu + \frac{1}{e}\partial_\mu \alpha$

And everything is fine…………

Lagrangian Formulation - QED

The free Dirac Lagrangian is, $\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi,$

The interacting Dirac Lagrangian is,

$$\begin{aligned}\mathcal{L}_{\text{QED}} &= \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{Maxwell}} + \mathcal{L}_{\text{int}} \\ &= \bar{\psi}(i\partial\!\!\!/ - m)\psi - \tfrac{1}{4}(F_{\mu\nu})^2 - e\bar{\psi}\gamma^\mu\psi A_\mu, \\ &= \bar{\psi}(iD\!\!\!\!/ - m)\psi - \tfrac{1}{4}(F_{\mu\nu})^2,\end{aligned}$$

where, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor

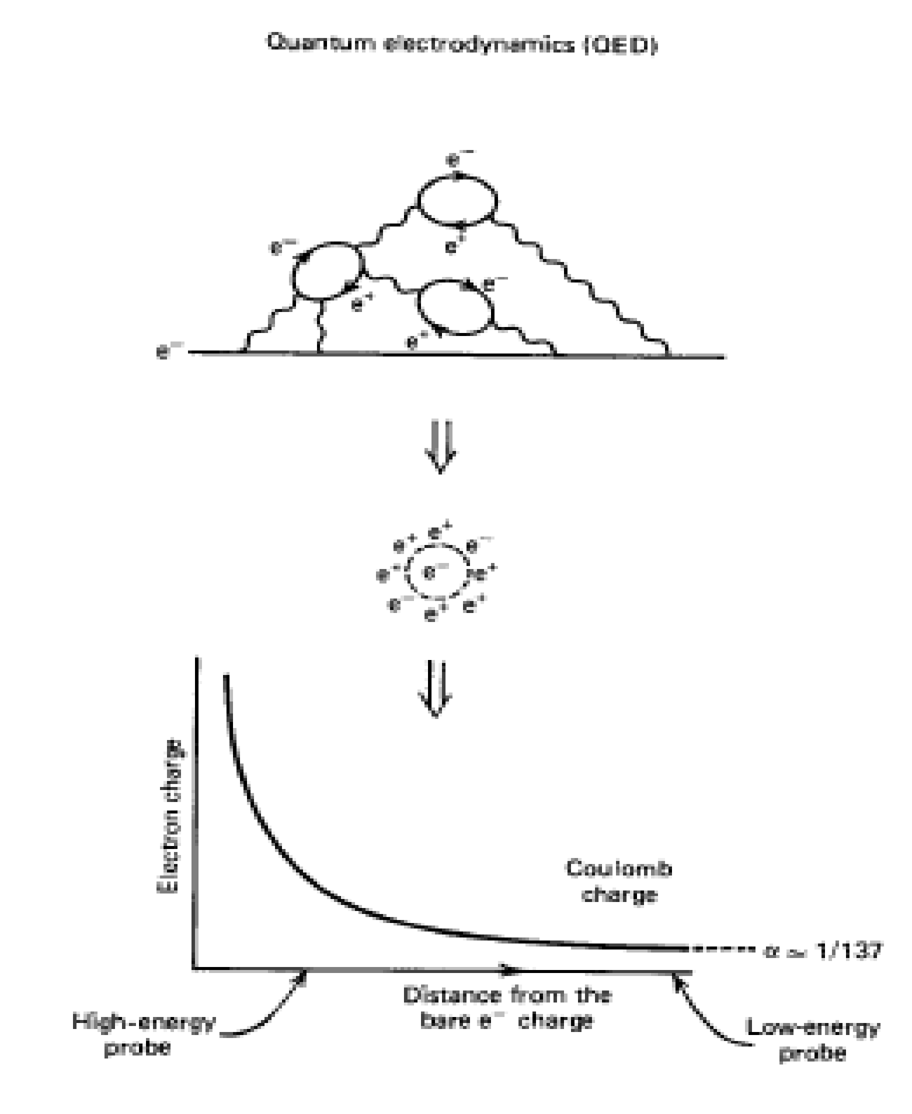
Note:

- The partition function $Z = N' \int \ldots [d\phi] \exp\left(\int_0^\beta d\tau \int d^3x\, \mathscr{L}\right)$

for free fermions and free photons give the correct F-D and B-E statistics.

- The coupling "e" is the bare coupling.

Lagrangian Formulation - QED



- We believe then that Z_{QED} gives the correct thermodynamics for the interacting fermions and photons.
- The effective QED coupling has a temperature dependence equivalent to that of energy scale dependence.

$$\alpha(|q^2|) = \frac{\alpha(0)}{1 - (\alpha(0)/3\pi)\ln(|q^2|/(mc)^2)} \qquad (|q^2| \gg (mc)^2)$$

Lagrangian Formulation - QCD

$L_{QCD} = L_{QED}$

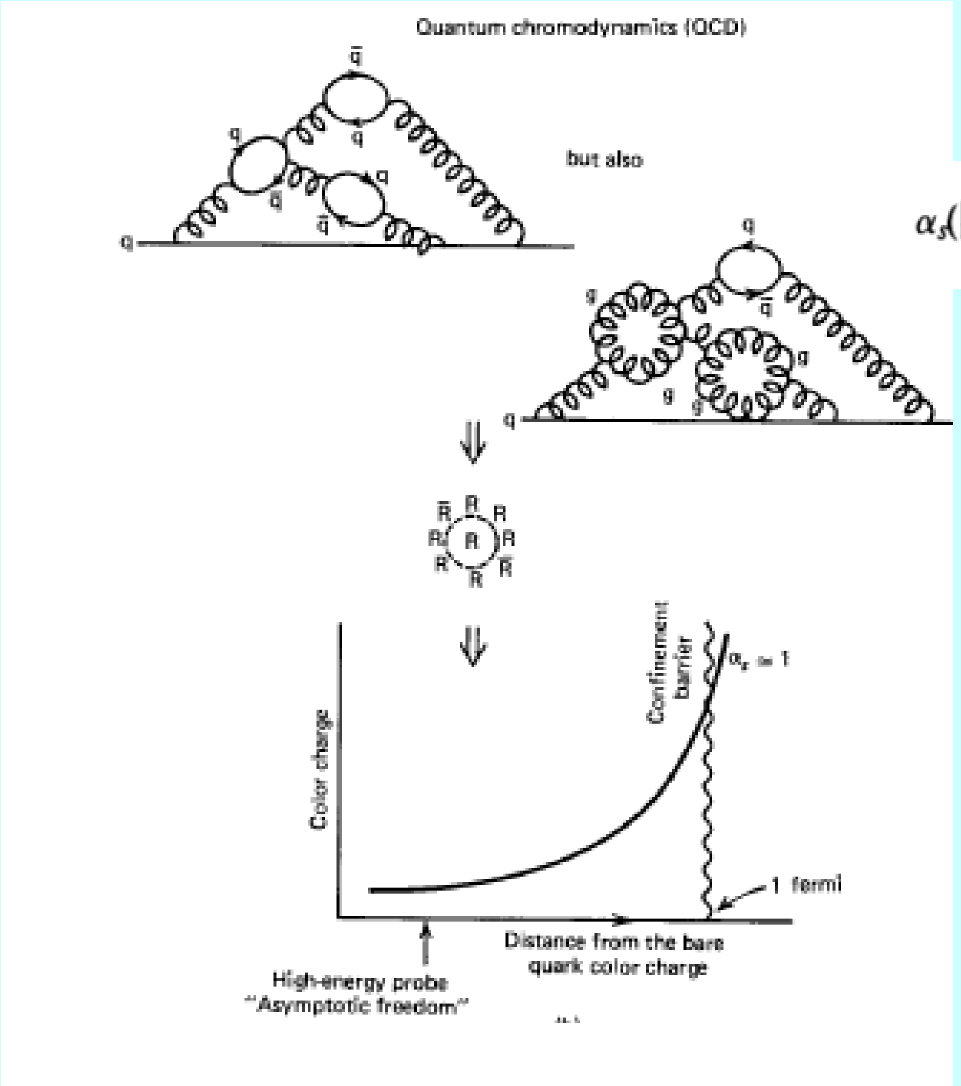
except that, $A_\mu = M^a A^a_\mu$ where the *M*'s are 3X3 Gell-Mann matrices

and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu],$

The *A*'s are the gluons mediating strong interaction.
The commutator displays the non-abelian character of the theory.

Here again we expect that a similar partition function can be utilized to study the thermodynamics of strongly interacting matter.

Lagrangian Formulation - QCD



- Non-abelian theories show Asymptotic Freedom

$$\alpha_s(|q^2|) = \frac{\alpha_s(\mu^2)}{1 + (\alpha_s(\mu^2)/12\pi)(11n - 2f)\ln(|q^2|/\mu^2)} \qquad (|q^2| \gg \mu^2)$$

- Defining

$$\ln \Lambda^2 = \ln \mu^2 - 12\pi/[(11n - 2f)\alpha_s(\mu^2)]$$

$$\alpha_s(|q^2|) = \frac{12\pi}{(11n - 2f)\ln(|q^2|/\Lambda^2)} \qquad (|q^2| \gg \Lambda^2)$$

$\Lambda \sim 1\text{GeV}$

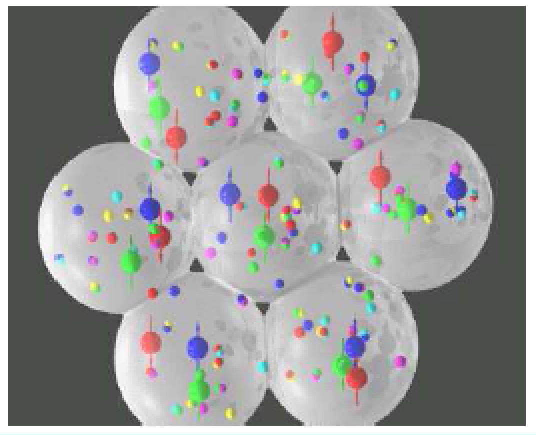
Scale of colour charge confinement

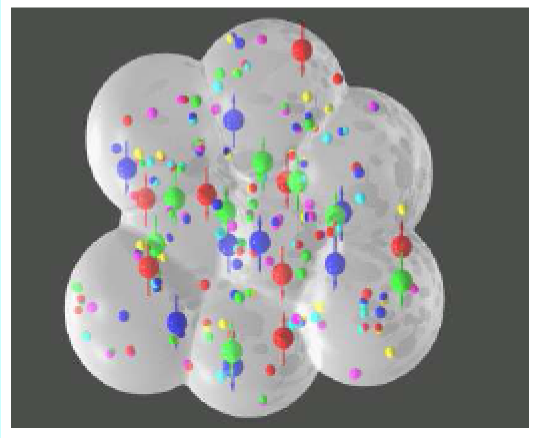
Observed in Lattice formulation of QCD (LQCD)

Thus we arrive at the first phase transition predicted from particle physics:

Confined Hadrons to Deconfined Quarks and Gluons at a temperature ~ 1 GeV

Standard model of cosmology estimates this to occur a micro-second after the Big Bang.





Lagrangian Formulation - QFD

$$L_{QFD} = L_{QED}$$

except that, $A_\mu = M^a A^a_\mu$ where the *M*'s are 2X2 Pauli matrices

and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$,

The *A*'s are the W and Z bosons mediating weak interaction
The commutator displays the non-abelian character of the theory

Here again we expect that a similar partition function can be utilized to study the thermodynamics of weakly interacting matter.
However there is something more …….

Lagrangian Formulation - QFD

….The W and Z bosons are massive !!

Vector boson mass ensures the short range of weak interaction but is detrimental to gauge invariance

The day was saved by Glashow, Weinberg and Salam (~1970) They introduced Higg's mechanism of spontaneous symmetry breaking (~1964) and the proof of renormalizability of massless and massive Yang-Mill's theory by 't Hooft (1971), to generate mass for W and Z bosons in a gauge invariant way.

- The theory describes the mass generation not only of W and Z bosons, but also of all the fermions before hadronization.
- The theory also finds that the coupling constants of weak and electromagnetic interactions become comparable for temperature T ~ Mw ~ Mz ~ 100 Gev.

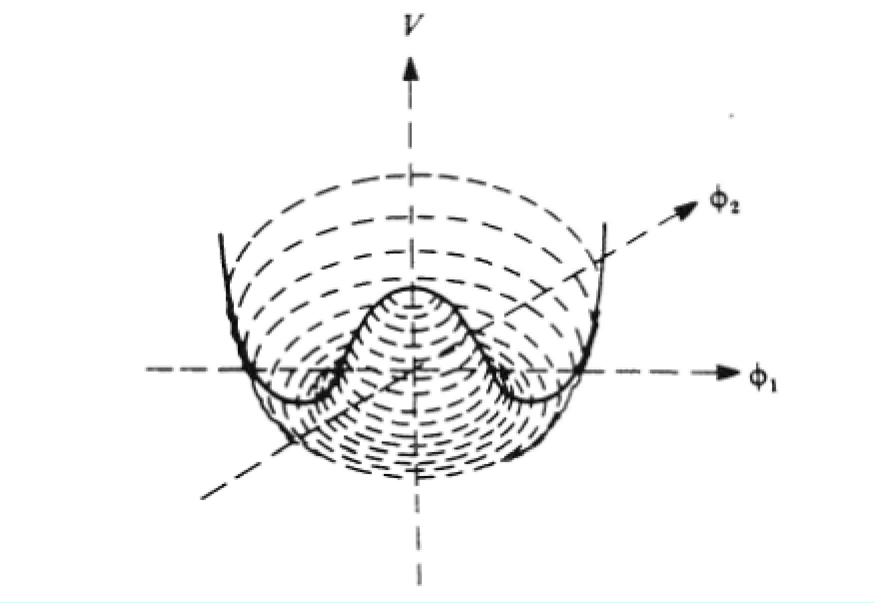
Spontaneous Symmetry Breaking

Let us consider the Lagrangian of a complex scalar field

$$\begin{aligned}\mathcal{L} &= (\partial_\mu \phi)(\partial^\mu \phi^*) - m^2 \phi^* \phi - \lambda(\phi^* \phi)^2 \\ &= (\partial_\mu \phi)(\partial^\mu \phi^*) - V(\phi, \phi^*).\end{aligned}$$

The classical ground state is obtained by minizing *V*

$$\frac{\partial V}{\partial \phi} = m^2 \phi^* + 2\lambda \phi^* (\phi^* \phi)$$



For m > 0, only soln. is

$$\phi = 0.$$

For m < 0, another soln. is

$$|\phi|^2 = -\frac{m^2}{2\lambda} = a^2,$$

Spontaneous Symmetry Breaking

Now consider the Lagrangian for a gauge theory

$$\mathcal{L} = (\partial_\mu + ieA_\mu)\phi(\partial^\mu - ieA^\mu)\phi^* - m^2\phi^*\phi - \lambda(\phi^*\phi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}.$$

A non-zero classical value of ϕ => a mass term for the gauge fields !!

Similarly, in the Fermion Lagrangian we may add

$$\alpha_\gamma\bar{\psi}\psi\phi.$$

A non-zero classical value of ϕ => a mass term for the fermion fields !!

Generalizing this scheme for SU(2) X U(1) symmetry, GSW obtained the satisfactory electroweak theory

Thus we arrive at the second phase transition predicted from particle physics:

Electromagnetic and Weak interaction gets unified at a temperature ~ 100 GeV

Standard model of cosmology estimates this to occur at ten pico-second after the Big Bang.

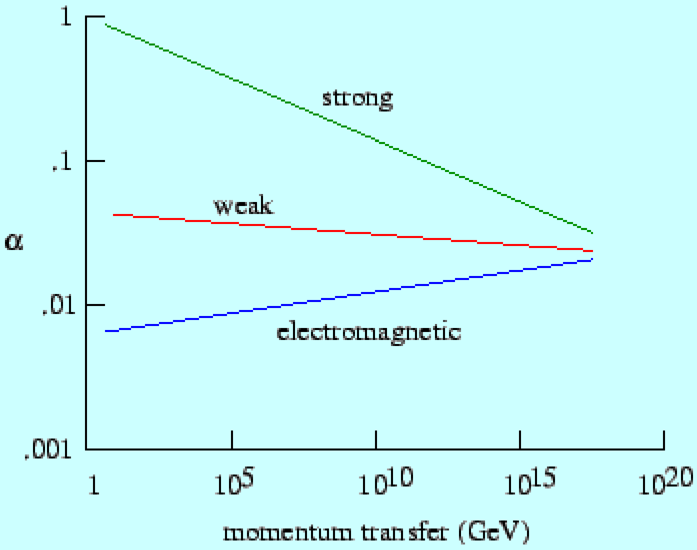
Massless photons Massive W and Z bosons	Massless photons as well as massless W and Z bosons

Where is Pr. Higgs ?

There is also this third phase transition *expected* from particle physics:

Electroweak and Strong interaction gets unified at a temperature ~ 10^{16} GeV

Standard model of cosmology estimates this Grand Unification to occur at 10^{-35} sec after the Big Bang.



- Quarks and Leptons would become indistinguishable!!

There is even this fourth phase transition ***expected***
from particle physics:

Standard model interactions and gravity gets unified at a temperature ~ 10^{19} GeV

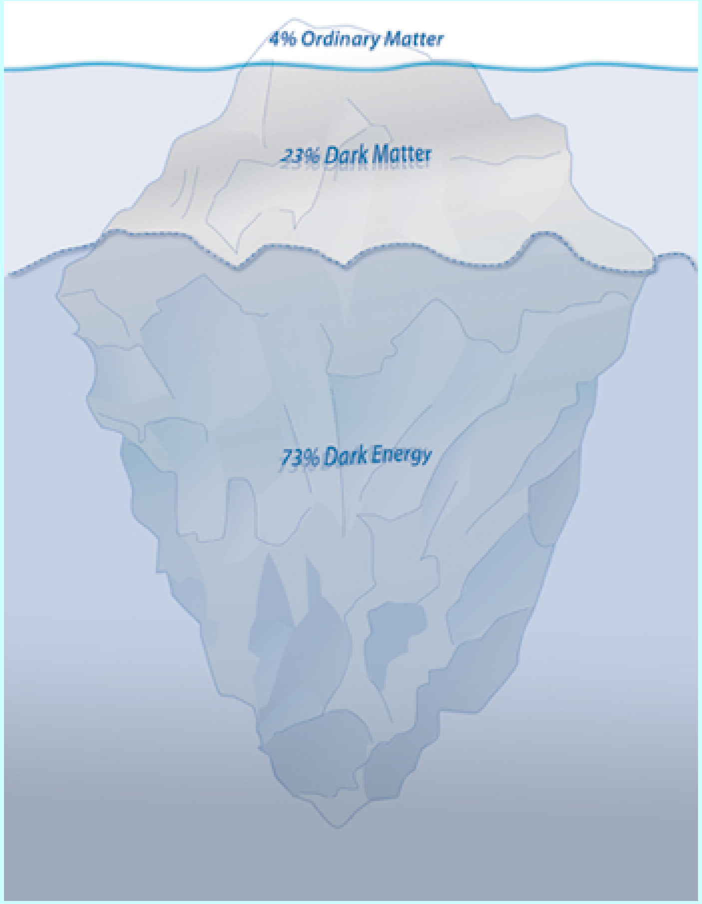
Standard model of cosmology estimates this Super Unification to occur at 10^{-43} sec after the Big Bang.

??????????????????????????
??????????????????????????
??????????????????????????

More particles !!!

- The mechanism of spontaneous symmetry breaking is associated with the generation of extended topological objects which are non-perturbative excitations of the theory. These are almost unavoidable in GUTs.
- Once upon a time these were supposed to generate the density fluctuation for structure formation.
- However none has been seen till date. This was among the various problems of standard cosmology.
- The inflationary cosmology gave a way out by diluting away these defects. However this does not reduce our burden as we are still far from a particle physics model for the inflaton.
- The topological defects, though fell out of favour as generators for large scale structure, may still contribute to dark matter and exotic events like generating ultra-high energy cosmic rays.

Thanks for your attention!!


4% Ordinary Matter
23% Dark Matter
73% Dark Energy