Introduction to Elementary Particle Physics

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Elementary Particle Physics

Lecture 2: Bahman 15, 1397

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Force	Strength	Range	Mediator
Strong	1	10^{-15} m (Nucleus size)	Gluon
EM	10^{-2}	Infinite	Photon
Weak	10^{-6}	10^{-18} m (Nucleon size)	$W^{\pm}$ and Z^0
Gravity	10^{-40}	Infinite	Graviton

Length Scales and Units

Scale in m			Scale in 10^{-18} m
10^{-10}	m	**Atom**	$100,000,000$
10^{-14}	m	**Nucleus**	$10,000$
10^{-15}	m	**Proton**	1000
$\leq 10^{-18}$	m	**Quark**	≤ 1

Length Scales and Units

	Scale in	m
Systems of planets (distance Earth-Sun)	10^{11}	m
Stars: Sun's radius	10^{9}	m
Planets, Earth's radius	10^{7}	m
Rocks, humans, $\cdots$	1	m
Grains of sands	10^{-3}	m
Viruses	10^{-7}	m
Simple molecules	10^{-9}	m
Atoms	10^{-10}	m

Length Scales and Units

Quantity	High energy Unit	Value in SI units
Length	1 fm	10^{-15} m
Energy	1 GeV=10^9 eV	1.602×10^{-10} J
Mass	1 GeV/c^2	1.780×10^{-27} kg
$\hbar = \frac{h}{2\pi}$	6.577×10^{-25} GeVs	1.054×10^{-34} Js
c	2.998×10^{23} fms^{-1}	2.998×10^{8} ms^{-1}
$\hbar c$	0.197 GeV fm	3.159×10^{-26} Jm

Length Scales and Units ($\hbar = c = 1$)

Mass	Mc^2/c^2	$\rightarrow 1$ GeV
Length	$\hbar c/Mc^2$	$\rightarrow 1\ \text{GeV}^{-1} = 0.197$ fm
Time	$\hbar c/Mc^3$	$\rightarrow 1\ \text{GeV}^{-1} = 6.57 \times 10^{-25}$ s

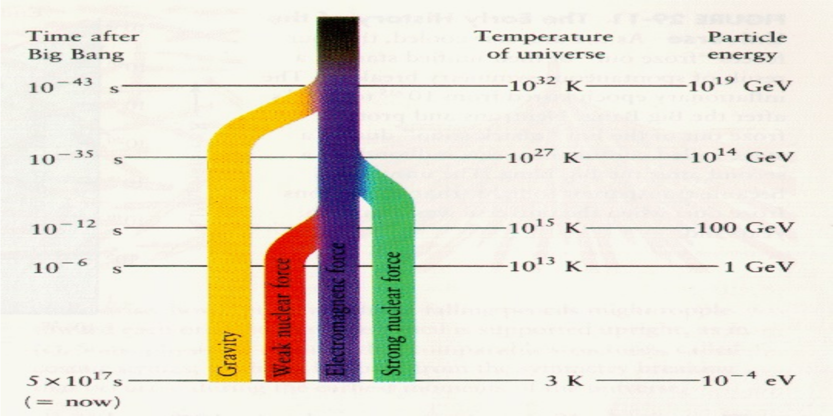
Lecture 2: Introduction

BIG BANG Cosmology

$$\sim 10^4 \text{ K} \sim 1 \text{ eV}$$

$$\sim 6.6 \times 10^{-25} \text{ s} \sim 1 \text{ GeV}^{-1}$$

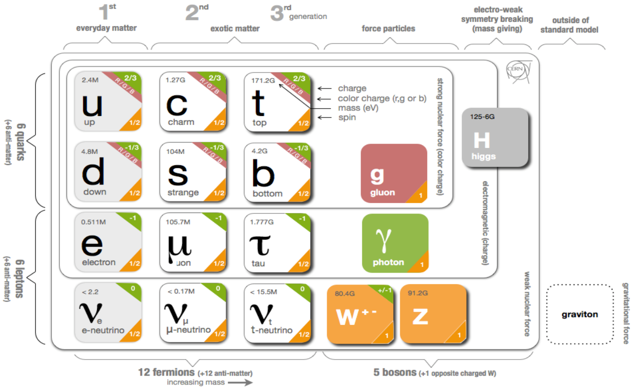
$$\sim 0.2 \text{ fm} \sim 1 \text{ GeV}^{-1}$$



Lecture 1: Introduction

Elementary Particle:

Definition: A particle is considered to be elementary only if there is no evidence that it is made up of smaller constituents



Standard Model of Particle Physics $\rightarrow$ Local Symmetries

$$SU(3_c) \times SU(2_f) \times U(1_{em})$$

Noether Theorem:

Global Gauge Invariance $\leftrightarrow$ Conserved Charges

Local Gauge invariance $\rightarrow$ Gauge fields (mediators) necessary

Question: Conserved charges .....?????

Symmetries:

- Space-time symmetries
  - **Continuous Lorentz transformation:** Rotation and boost
    Lorentz+translation invariance $\rightarrow$ Poincaré invariance
  - **Discrete Lorentz transformation:** Parity, time reversal

- Internal symmetries
  - Global transformation: Global $U(1)$ and $SU(N)$
    $\curvearrowright$ **Conservation of (electric) charge**
  - Local transformation: Local $U(1)$ and $SU(N)$
    $\curvearrowright$ **Gauge fields** (force carriers)

Gauge fields and local gauge symmetry:

Maxwell's equations

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}, \qquad \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0,$$

$$\nabla \cdot \mathbf{B} = 0, \qquad \nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$$

$$\mathbf{B} = \nabla \times \mathbf{A}, \qquad \mathbf{E} = -\nabla\phi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}$$

Maxwell's equations are invariant under "gauge transformation":

$$\begin{aligned} \mathbf{A} &\rightarrow \mathbf{A}' = \mathbf{A} + \nabla\Lambda \\ \phi &\rightarrow \phi' = \phi - \frac{1}{c}\frac{\partial \Lambda}{\partial t} \end{aligned}$$

Gauge fields and local gauge symmetry:

Schrödinger equation in the presence of EM fields:

$$\left[\frac{1}{2m}\left(\frac{\hbar}{i}\boldsymbol{\nabla} - \frac{e}{c}\mathbf{A}\right)^2 + e\phi\right]\psi(\mathbf{x}, t) = i\hbar\frac{\partial}{\partial t}\psi(\mathbf{x}, t)$$

This equation is only invariant if $\psi(\mathbf{x}, t)$ transforms as

$$\psi'(\mathbf{x}, t) = \exp\left(\frac{ie}{\hbar c}\Lambda(\mathbf{x}, t)\right)\psi(\mathbf{x}, t).$$

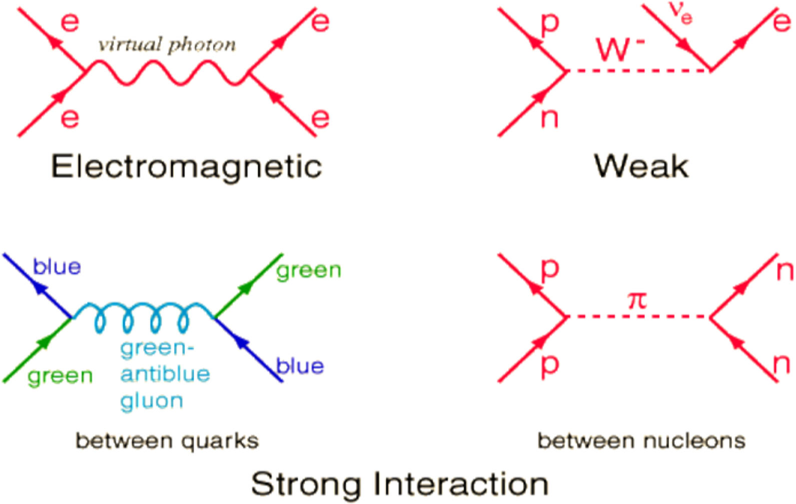
Hence, together with

$$\begin{aligned} \mathbf{A} &\rightarrow \mathbf{A}' = \mathbf{A} + \boldsymbol{\nabla}\Lambda, \\ \phi &\rightarrow \phi' = \phi - \frac{1}{c}\frac{\partial\Lambda}{\partial t}, \end{aligned}$$

the Schrödinger equation is invariant under

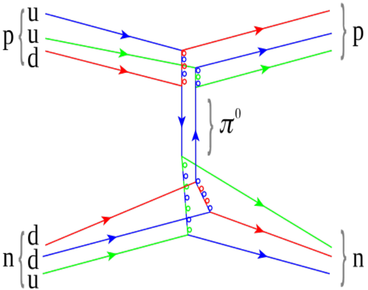
local U(1) gauge transformation

Lecture 2: Introduction



Color charge → Strong force

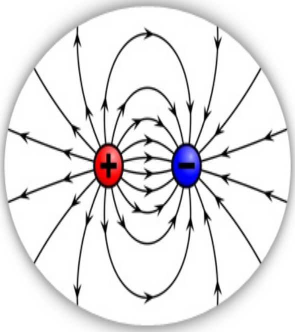
Color charge → Strong force

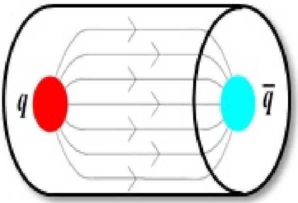


Strong Force

Strong Force vs. Electromagnetic Force

- Flux line (QED) vs. Flux tube (QCD)

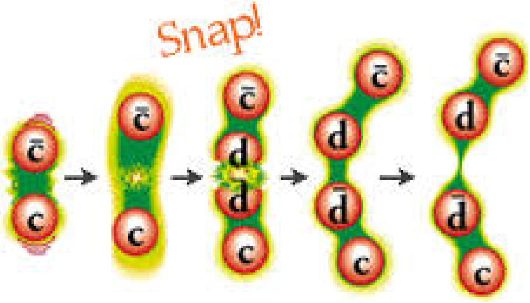




  - Static quark potential: $V(r) = \sigma r + \frac{\alpha(r)}{r}$

Strong Force vs. Electromagnetic Force

- Confinement



Color charges in the singlet state are not free
(at low energy)